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THEORETICAL AND FIELD WATERFLOOD PERFORMANCE, KANE SAND, KANE OILFIELD, ELK COUNTY, PA.

By Leo A. Schrider, John R. Duda, and Harry R. Johnson

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
1967

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Walter R. Howard

Director

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* * * * * * * * * * * * report of investigations 6917

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THEORETICAL AND FIELD WATERFLOOD PERFORMANCE, KANE SAND, KANE OILFIELD, ELK COUNTY, PA.

by

Leo A. Schrider,[1] John R. Duda,[1] and Harry R. Johnson[2]

ABSTRACT

A prediction for oil recovery from a pilot waterflood in the Kane oilfield, located in Elk, Forest, and McKean Counties, Pa., was made and compared to actual field performance.

Water-injection and production histories, well logs, other field data, and results from laboratory tests of core material were used in this analysis. Performance of the pilot waterflood, initiated in January 1963, was predicted using a modified Craig, Geffen, and Morse calculation technique. Maximum recovery from this low permeable, preferentially oil-wet formation was predicted to be about 22,500 barrels of oil after 300,000 barrels of water had been injected into the pilot waterflood area. After additional field data were collected it became necessary to reevaluate the pilot waterflood area. The gas saturation prior to the waterflood was estimated to have been 20 percent, based on an assumption regarding the required volume of water injected to initiate oil production. In view of the actual field performance, a gas saturation of 13 percent is indicated. When this gas saturation and the method originally proposed by Craig and others are used, the predicted results are more representative.

In December 1965, field performance was further analyzed using a hyperbolic-decline curve as presented by Arps. Based upon this evaluation method, the pilot waterflood in the Kane sand should produce 37,000 to 42,000 barrels of oil with the injection of 300,000 barrels of water into the pattern. By continuing this secondary-recovery project to a reasonable economic limit, ultimate oil recovery may be as much as 50,000 to 55,000 barrels, or 129 to 142 barrels per acre-foot from 36.5 acres.

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INTRODUCTION

The Bureau of Mines is studying selected Appalachian area reservoirs to determine their susceptibility to secondary recovery. The objective of this work, which is detailed in an earlier report (25),[3] is to increase the recovery of oil from known pressure-depleted reservoirs.

Recent reports dealing with the Kane oilfield, which was selected for study under this program, describe the reservoir data (7), a prediction for oil recovery from a pilot waterflood area (4), and a progress report of the field performance (12).

This report presents a complete study of the Kane sand project and compares the theoretical and actual field waterflood performance. Two wells were cored in the pilot waterflood area; one by the operator, Fords Brook Drilling Company, and the other by the Bureau of Mines. The core analyses, well logs, and field production data were used to predict the performance of this secondary-recovery waterflood project. Following 3 years of injection-production data, a comparison of the original prediction with the actual performance and subsequent reevaluation of the project was accomplished.

ACKNOWLEDGMENTS

The authors acknowledge the suggestions of Dr. E. T. Heck, consultant and vice president, Minard Run Oil Company, Bradford, Pa., and the cooperation of Mr. Knight Thornton, Thornton Producing Company, Wellsville, N.Y., who generously provided much of the data for this report. Recognition is also given to the Bureau of Mines Industry Technical Advisory Committee for their suggestions concerning this study.

GEOLOGY

The Kane oilfield, approximately 12 miles long and 1 mile wide, is located in parts of Elk, Forest, and McKean Counties, Pa. (fig. 1), along the northwestern flank (of the surface axis) of the Smethport anticline (17). The topography of the area is composed of broad, flat summits that slope gradually into narrow valleys (3). The maximum relief is about 400 feet.

Surface rocks on the summits belong to the Allegheny and Pottsville Series of the Pennsylvanian system, while outcrops along the major stream beds belong to the Pocono Group of the Mississippian system. These surface beds dip gently (2° to 3°) to the northwest from the western flank of the Smethport anticline. Gas is produced along the anticlinal axis, and oil is produced further down the structure along the northwestern flank.

Initial oil production was from the Nansen, Sackett, and Duhring pools which were discovered about 1881. Subsequent development combined these into the Kane oilfield. Drillers in the area correlated the Kane sand of this

[3] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

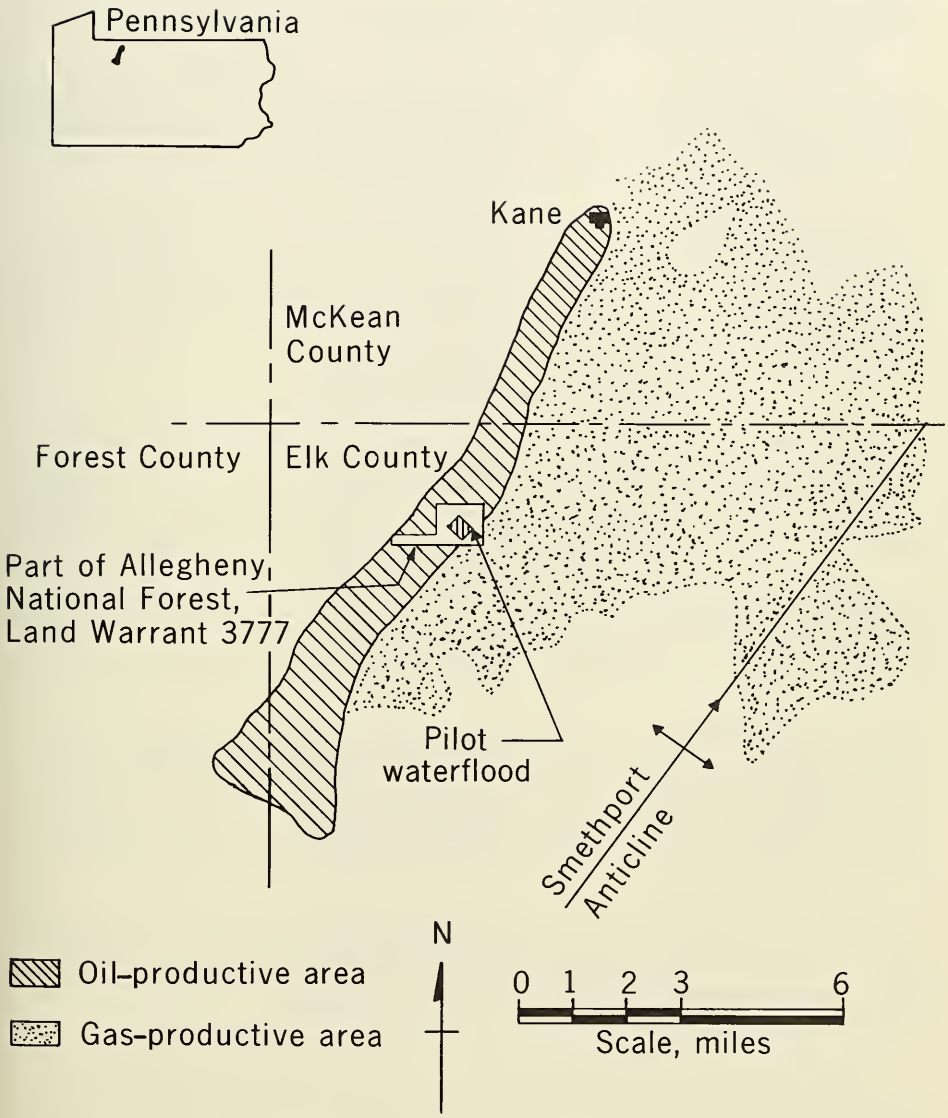

FIGURE 1. - Kane Oilfield, Highland Township, Elk County, Pa.

field with the Kane sand found in the Bradford District, McKean County. Fettke (14) later confirmed this correlation.

The Kane sand is in the Upper Devonian system at a depth of approximately 2,200 feet. The sand is gray to medium-brown in color, very fine- to fine-grained, slightly calcareous, shaly, and well cemented. Stratigraphically, it is approximately 120 feet below the Bradford Third sand, which is oil productive 25 miles to the north.

In 1928, an exploratory well drilled to 7,930 feet in the Kane field was located about 3 miles northeast of the pilot waterflood area. Fettke (14) recorded the geological formations at this location from sample cuttings, and his identification of the formations through the bottom of the Kane sand are shown in figure 2. The Upper Kane sand in figure 2 would be correlative with the Kane sand in the pilot waterflood area.

LEASE HISTORY AND DEVELOPMENT

Published records (20) show that the first successful oil well in the Kane field was drilled in 1881. Nine years later, the first well was drilled on the portion of Land Warrant 3777 covered in this report (fig. 1). By January 1891, 17 wells had been drilled; and by October 1900, the development was completed with an additional 52 oil wells on approximately a 10-acre spacing.

Each well was equipped with 300 to 500 feet of 5-5/8-inch casing, to exclude surface water, and was drilled through the producing sand. The wells were shot with approximately 100 quarts of nitroglycerin set 10 feet below the top of the pay sand and the completed open hole and were equipped with tubing, bottom-hole pumps, and sucker rods.

Lytle (20) reported that the initial production rates in the Kane field were as high as 100 barrels per day per well. The average production rates for the 10-year period, prior to waterflooding, were less than 1 barrel per day per well in Land Warrant 3777 with producing gas-oil ratios ranging from 200 to 500 scf per barrel. Estimates of cumulative oil production range from 6,000 to 14,000 barrels per well. No water was produced prior to initiation of the pilot waterflood.

Oil production from Land Warrant 3777 is shown in figure 3. Production records before 1904 were not available. The production curve for the period 1904 through 1934 is based on average yearly production for 5-year intervals. The sharp upswing in production in 1963 was due to the initiation of the pilot waterflood.

Original reservoir energy in this field is attributed to a combination solution-gas and gas-cap drive. Production of the gas cap and subsequent shrinkage has inactivated the gas-cap drive and permitted the oil to migrate up dip into the original cap area. Oil production from wells that originally produced only gas is evidence of this migration. Not all of this oil is recoverable by natural means since a portion will become residual oil in the invaded gas sand.

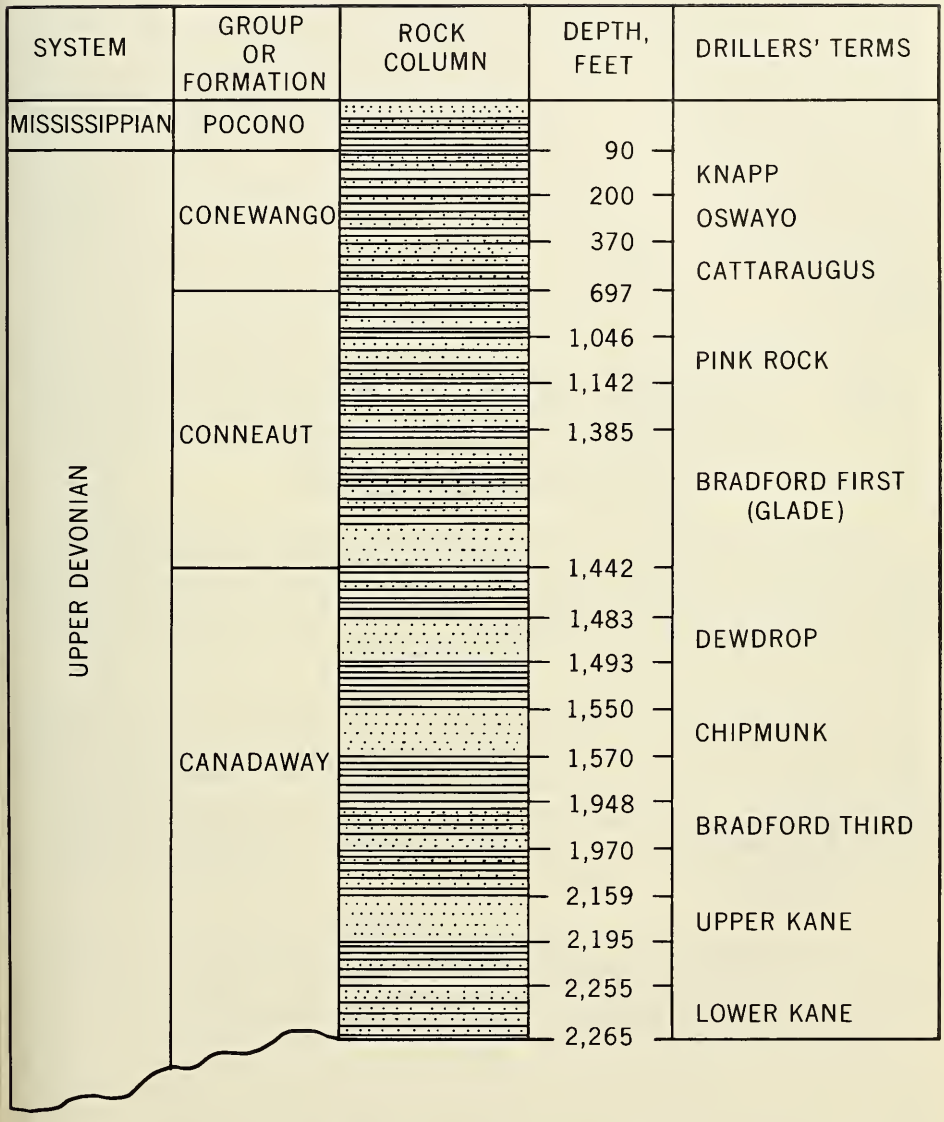

FIGURE 2. - Columnar Section of Geological Formations in the Kane Oilfield.

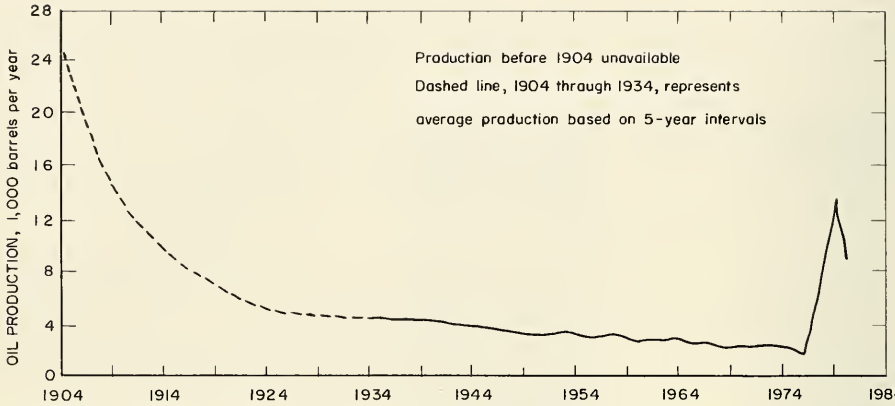

FIGURE 3. - Annual Oil Production, Part of Land Warrant 3777, Allegheny National Forest, Highland Township, Elk County, Pa.

DEVELOPMENT OF PILOT WATERFLOOD

The operator chose a location for the pilot waterflood where the wells, for the most part, were already drilled. The spacing and location of the wells selected for the test are shown in figure 4. This area consists of nine injection and four producing wells enclosing an area of 36.5 acres. Old producing wells were converted to injection wells and new producing wells were drilled and completed, resulting in four normal five-spot patterns.

All wells in the pilot project were subsequently hydraulically fractured, using 300 to 500 barrels of water and 9,000 to 12,000 pounds of sand. Treating pressures in the four new wells were about 800 psig less than in the old wells, due to the use of 3-inch tubing in the new wells as opposed to 2-inch tubing in the old. The average breakdown and treating pressure were about 4,500 and 3,000 psig, respectively. Before fracturing, the wells produced only a few gallons of oil per day; after fracturing, they produced a few barrels per day. The major increase in production was not experienced until fill-up occurred.

Water injection began in January 1963 when surface water was injected into the Kane sand at rates shown in table 1. This water was treated with a corrosion inhibitor and injected at a wellhead pressure ranging from 1,500 to 1,700 psig. In January 1966, a pressure of 1,600 psig was being used.

An unusually large amount of water was produced in June and July of 1963. (See table A-1 for complete pilot-flood injection-production history.) This large volume of water which broke through was attributed in part to fractures which the operator believed existed between injection and production wells. This was later confirmed in August 1963 when the operator injected slugs of fluorescein dye into the injection wells. The extremely short time (1 to 3 days) required to produce the injected dye confirmed the existence of

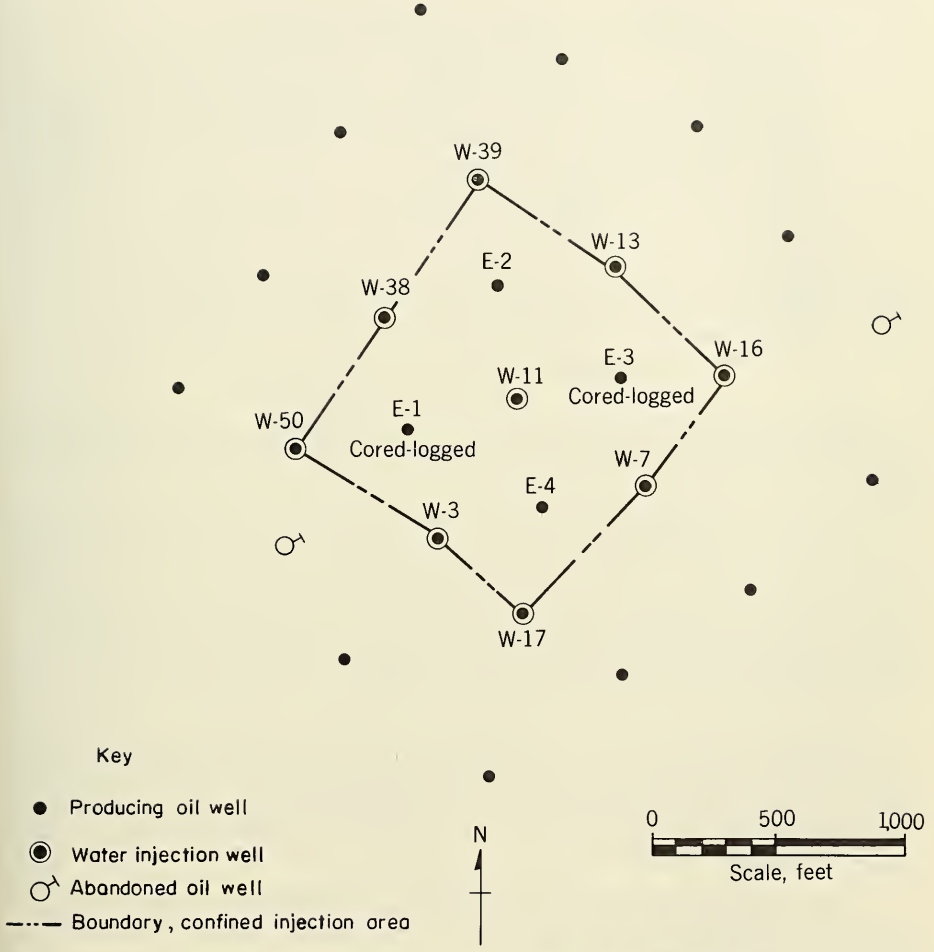

FIGURE 4. - Pilot-Flood Area and First-Line Offset Wells.

fractures or near-miss fractures. The application of this test and additional tracer tests conducted by the Bureau of Mines are discussed later in this report.

TABLE 1. - Initial water-injection rates

Injection well	Month of initial injection (1963)	Rate of injection in April 1963, average bbl per day
W-16.....	....January.....	81
W-17.....	.....do.....	110
W-39.....	.....do.....	20
W-50.....	.....do.....	58
W-7.....	....February....	87
W-13.....	.....do.....	79
W-38.....	.....do.....	49
W-3.....	....March.....	111
W-11.....	....April.....	144

CORING AND LOGGING OPERATIONS

Producing wells E-1 and E-3 (fig. 4) were cored and logged. Well E-1 was cable-tool cored using dextrose water as the drilling fluid and well E-3 was rotary cored with air. Electrical and nuclear logs were obtained from both wells.

A diamond air-rotary core with a 3-1/2-inch diameter was taken from well E-3 in November 1962. A total of 35.5 feet of Kane formation was cored, but only 23.7 feet of core was recovered; the remainder (11.8 feet) was drilled up during coring operations. While the core was being removed from the barrel, 13.1 feet of it fell through the derrick floor and could not be placed in proper sequence after it was recovered. Therefore, the core analysis for well E-3 is based on lithology and is shown in table A-2.

The Kane sand was also cored in well E-1 with a cable-tool core barrel using dextrose water. This core was taken in September 1962 and was analyzed by a commercial laboratory. Results of the core analysis for E-1 are shown in table A-3. The top of the Kane sand was encountered at 2,314.3 feet in well E-1 and the bottom was encountered at 2,350.4 feet, resulting in a gross sand thickness of 36.1 feet.

At the completion of coring operations, wells E-1 and E-3 were logged using a low water-loss mud. The series of well logs used to evaluate well E-3 is shown in figure 5.

Electrical logs were run through the Kane sand in all producing wells (E-1 through E-4) and were used to evaluate and correlate this sand throughout the pilot waterflood area. Figure 6 shows a diagram of the resistivity logs and the excellent correlation that exists between the producing wells. All of the logs indicate that the Kane sand is approximately 36 feet thick. These electric logs and cores from wells E-1 and E-3 also show that the sand is heterogeneous with a significant amount of shale interbedding. Consequently, all of the formation cannot be considered floodable or effective sand. The well logs indicate further that approximately 16 feet of the formation is shale. These shale streaks separate the remaining 20 feet of formation into thin sand

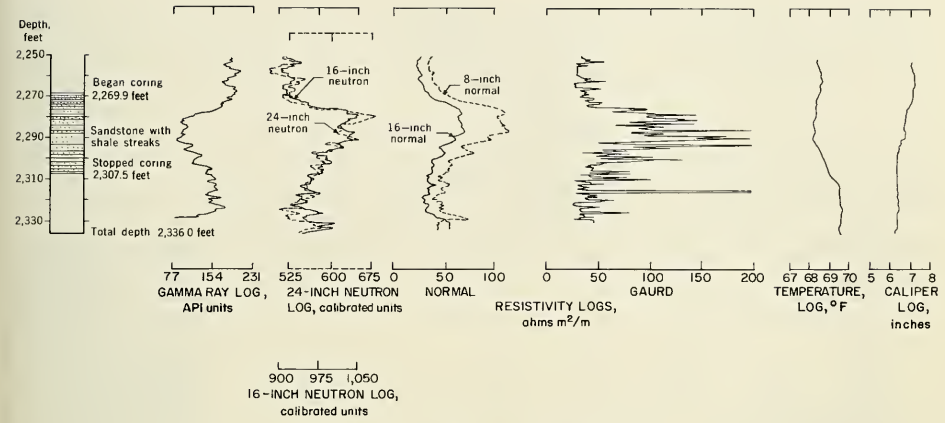

FIGURE 5. - Well Logs for Well E-3.

lenses. Fracturing this interbedded section by the method previously described has contributed materially to the success of this waterflood.

CORE ANALYSIS

Only 60 percent of the core was recovered from well E-3, thus the sequence of formation characteristics is undistinguishable in this well. This core analysis, therefore, cannot be used to evaluate the sand with any degree of reliability. In well E-1, however, 95 percent of the core was recovered. Approximately 96 percent of the total injection capacity of well E-1 is contained in the sand intervals with air permeabilities above 1 md. For all practical purposes, the total of these intervals (10.6 feet) is the effective sand thickness. The weighted-average air permeability of this effective sand is 4.4 md. Table 2 summarizes the core and log analyses of wells E-1 and E-3. Core analysis procedures were described in a previous report (25).

TABLE 2. - Results of core and log analyses, Kane sand

	Well E-1		Well E-3		Average
	Core	Log	Core	Log	
Oil saturation.....percent pore volume	30.4	-	27.0	-	28.7
Water saturation.....percent pore volume	11.9	14.0	8.9	13.4	[1]13.2
Porosity.....percent	10.8	10.3	12.1	11.0	[1]10.8
Air permeability.....millidarcy	4.4	-	5.7	-	[2]4.4
Effective sand thickness.....feet	10.6	-	-	-	10.6

[1]Based on the average of core and log analyses of well E-1 and log analysis of well E-3.

[2]Based on results of core analysis of well E-1.

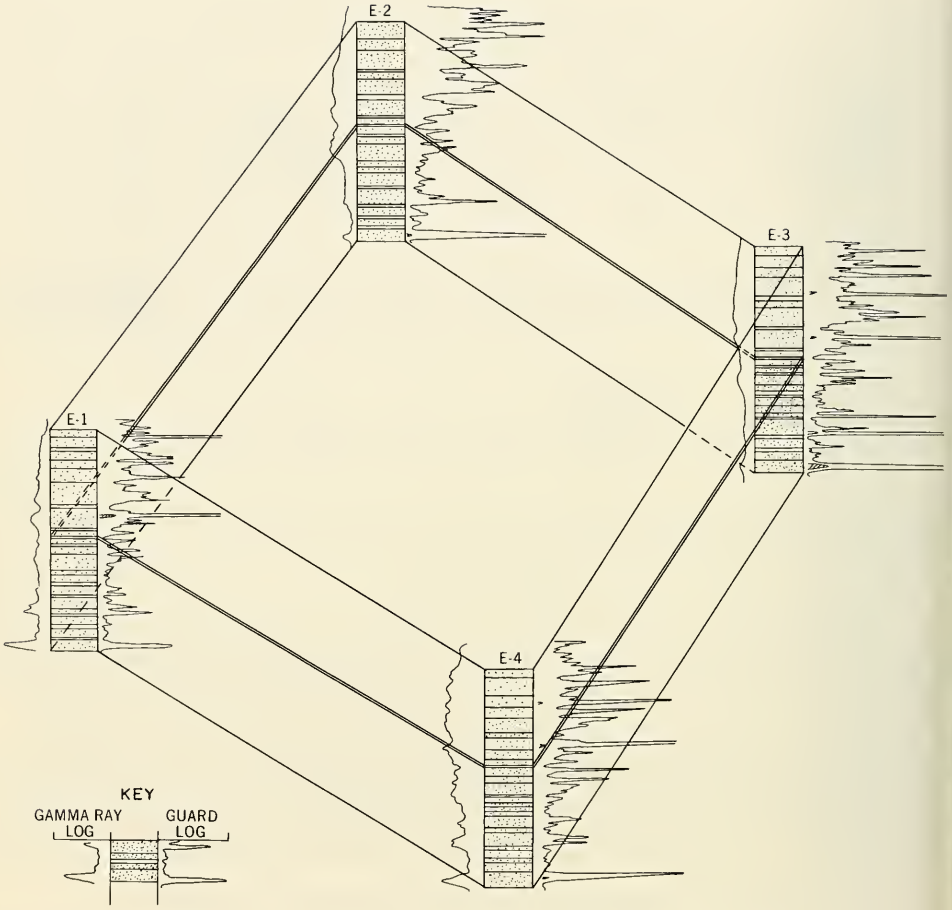

FIGURE 6. - Diagram of Sand Development in the Pilot Waterflood Area.

Wettability and Relative Permeability

Representative core samples of the Kane sand were tested to determine preferential wettability. Five pairs of adjacent samples were chipped from the fresh core obtained from well E-3. One sample of each pair was immersed in oil and the other in distilled water. The initial rate of water or oil imbibition into each sample (21) and the total amounts imbibed were determined. The results are given in table 3. The Kane sand samples imbibed both oil and water; however, oil was imbibed much faster than water and also in greater

volume. Water will not enter the smaller pore channels of a preferentially oil-wet system (21) because capillary forces causing imbibition are greater for oil than for water. This behavior was exhibited by the samples taken in the Kane sand, indicating it to be a preferentially oil-wet system.

TABLE 3. - Results of imbibition tests

Sample	Oil imbibed		Water imbibed	
	Initial rate, pore volume per hour	Total, fraction of pore volume	Initial rate, pore volume per hour	Total, fraction of pore volume
1.....	0.59	0.30	0.34	0.07
2.....	.73	.48	.64	.15
3.....	.95	.66	.52	.25
4.....	1.39	.76	.20	.15
5.....	1.35	.54	.81	.37
Average..	1.00	.55	.50	.20

Rock wettability can also be determined by comparing measured pore volumes of samples saturated with helium, oil, and water. It would be expected that saturation of samples with water would be less complete than with oil in an oil-wet system (9). For this test, 13 samples from the effective sand interval were saturated with oil, and 13 adjacent samples were saturated with brine. Helium pore volumes, determined before saturation, were used as the standard for comparison of the pore volumes determined gravimetrically. Statistically, no difference existed between pore volumes measured by helium and those measured by oil saturation, indicating that oil had completely wet the system. However, the average pore volume of the 13 samples determined by water saturation was only 85 percent of the average pore volume determined by helium.

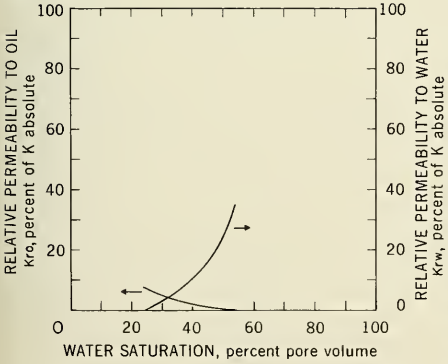

FIGURE 7. - Average Water-Oil Relative-Permeability-Ratio Curves for the Kane Sand, Well E-3.

The relative-permeability characteristics of a reservoir also reflect the effect of wettability (15). In a preferentially oil-wet system, oil flows near the surface of the sand grains and in the smaller pore channels, while water flows near the center of the larger pore channels. Since the flow of oil is more restricted than the flow of water in such a system, the relative permeability to water at residual oil saturation should be greater than the relative permeability to oil at residual water saturation. This characteristic of a preferentially oil-wet system is shown in the average water-oil relative-permeability curves (fig. 7) for two core samples from well E-3. The relative-permeability tests

were performed using the procedure described by Loomis and Crowell (19). The individual curves were calculated using the technique described by Higgins (15):

where:

Krw = relative permeability of the water at the residual oil saturation, percent of K absolute,

Kro = relative permeability of the oil at the irreducible minimum water saturation, percent of K absolute.

The average relative permeability to water at residual oil saturation is 4.7 times greater than the relative permeability to oil at residual water saturation.

Gas-oil relative-permeability characteristics were also determined for the effective sand interval in well E-3. The average gas-oil relative-permeability-ratio curve of four samples is shown in figure 8.

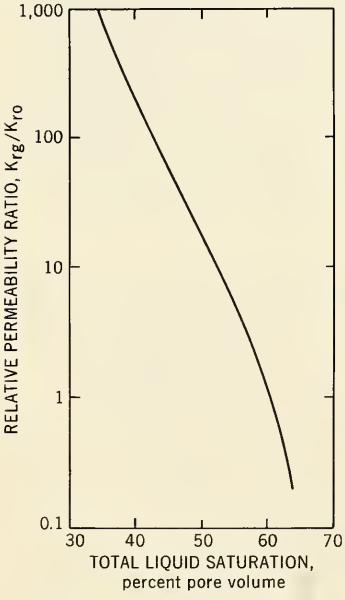

FIGURE 8. - Average Gas-Oil Relative-Permeability-Ratio Curve for the Four Samples of Kane Sand, Well E-3.

Fluid Saturations

The average water saturation determined by log and core analyses of well E-1 and log analysis of well E-3 was 13.2 percent (table 2). This water is immobile since water is not produced from the Kane sand.

The journal article published in August 1964 (4) predicted the oil recovery from the pilot waterflood area using an assumed gas saturation of 20 percent. (This prediction was necessarily based on several assumptions, and the assumed gas saturation was apparently too high.) The field data now indicate that an initial gas saturation averaging about 13 percent existed in the Kane sand reservoir. One reason for the difference between the actual and the predicted performance of this waterflood was the inability to establish fluid saturations by a material balance of the produced fluids, and another reason is the assumption made regarding the fill-up volume. The latter assumption will be discussed later in this report. Based on current knowledge, the oil saturation prior to initiation of the waterflood would have been 73.8 percent. The residual oil saturation from relative-permeability tests is 46.3 percent (fig. 7).

Reservoir-Fluid Properties

The Kane oilfield was almost completely developed before 1900; consequently, no analysis of the original reservoir fluids is available. A stock-tank sample of oil was taken from well E-1 in November 1962. The measured viscosity and specific gravity of the sample was 3.05 cp and 0.795, respectively, and the API gravity was 44.7°. All tests were made at the bottom-hole temperature of 80° F.

PREDICTION METHOD

The method originally employed to predict secondary recovery of oil from this area by waterflooding was that proposed by Craig, Geffen, and Morse with a modification in the injected volume of water required to initiate oil production (4). In the paper by Craig and others (10), it was assumed that all of the free-gas space within the confined area should be liquid filled before oil production begins. In preparing the Kane sand prediction, however, the authors assumed that only the gas space in the initially swept area should be liquid filled. Other authors (13, 23) state that all of the gas space must be liquid filled. It was therefore necessary to reevaluate the pilot waterflood prediction.

This reevaluation was made using a composite of the original method used by Craig and others and that proposed by Suder and Calhoun (24). The Suder-Calhoun technique, based on Darcy's radial-flow equations and a material balance of the injected fluid, was applied up to water breakthrough. This results in a realistic profile of water-injection rates until the beginning of the steady-state flow.

After water breakthrough, emphasis was placed on the method originally proposed by Craig and others. This method accounts for continued oil production from the invaded region through the use of the frontal-advance equation proposed by Buckley and Leverett (5) and modified by Welge (26). Also considered is oil production from the newly invaded region as the areal sweep efficiency increases with continual water throughput. The data required to perform these calculations are presented in table 4.

TABLE 4. - Data required to calculate pilot waterflood predictions

Oil viscosity	3.05 cp
Water viscosity at reservoir conditions	1.0 cp
Relative permeability characteristics	(See fig. 7)
Interstitial water saturation	13.2 percent pore volume
Gas saturation before water injection	13 and 20 percent pore volume
Total area flooded	36.5 acres
Thickness	10.6 feet
Porosity	10.8 percent
Absolute permeability	3.2 md
Distance between injection wells	635 feet
Effective wellbore radius	approximately 10 feet
Pressure at the sandface	2,500 psig
Pore volume of confined area	324,000 bbl
Oil formation-volume factor	1.05
Assumed water-injection rate after January 31, 1966	11,600 bbl per month

PREDICTED AND ACTUAL WATERFLOOD PERFORMANCE

Figure 9 is a plot of the dimensionless oil production-water injection rate as a function of the cumulate water injected. The predicted performance for gas saturations prior to waterflooding (13 and 20 percent) is compared to the actual field performance of the waterflood. This method of presenting the data was chosen so that conditions controllable by the operator, such as injection rate and pump failure, do not enter into the analysis. The curves were developed by dividing the instantaneous oil-production rate by the instantaneous water-injection rate for any given amount of cumulative water injected. For example, in July 1964 the cumulative water injection was 325,155 bbl (table A-1). The monthly oil-production rate (1,206 bbl) was divided by the monthly water-injection rate (15,061 bbl) to yield a value of 0.08 which is then plotted on figure 9 versus the cumulative water injected (325,155 bbl).

It is readily apparent from figure 9 that the original estimated gas saturation of 20 percent (4) yields low production-rate values. This is further confirmed in figure 10 which indicates a low cumulative oil recovery as compared to the actual recovery.

The difference between the originally predicted results (using 20-percent gas saturation) and the actual field data is believed to be due to an assumption made in developing the original prediction. It was assumed that only the gas space in the initially swept portion of the reservoir should be liquid filled in order to initiate response at the producing wells. The theoretical minimum gas saturation that existed in the reservoir was then established by noting the volume of water injected until a response at the production wells

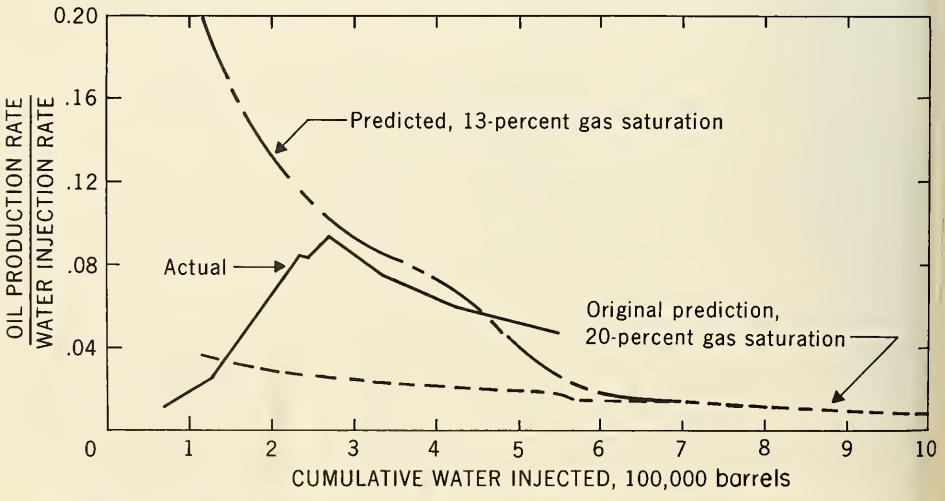

FIGURE 9. - Predicted and Actual Field Performances, Pilot Waterflood, Kane Oilfield, Elk County, Pa.

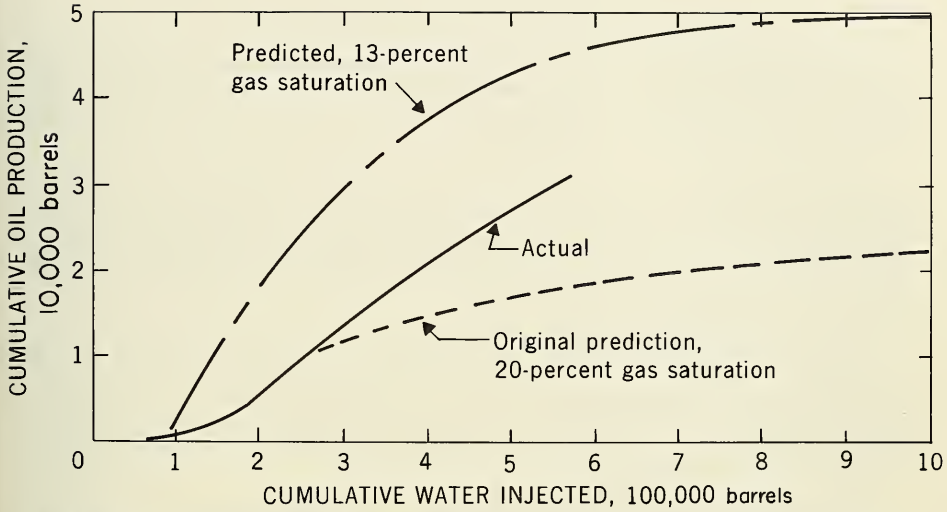

FIGURE 10. - Cumulative Oil Recovery Using Predicted and Actual Field Results, Pilot Waterflood, Kane Oilfield, Elk County, Pa.

was observed. The pilot waterflood indicated this response by June 1963, and a gas saturation of approximately 20 percent was calculated. When these same field data are viewed under the assumption that all of the gas space within the confined area must be liquid filled, an initial gas saturation of about 13 percent was calculated. Although a gas saturation of 13 percent is now accepted as approximately correct, the results of prediction calculations using this figure still do not match actual performance. In making the calculations, the Kane sand was assumed, for purposes of simplification, to consist of a single, homogeneous layer. Such an assumption is weak for several obvious reasons. Because this sand is highly stratified, the injected water can move through the sand at varying rates depending on the permeability of the individual strata, and breakthrough will not occur simultaneously in all layers. Perhaps a more important factor in the discrepancy between actual and predicted results is the fact that the wells were hydraulically fractured during completion. Some of these fractures provided almost direct communication between injection and production wells. As a result, a very early water breakthrough was experienced and a percentage of the injected water has done little or no work in displacing oil. The areal sweep efficiency and displacement efficiency have improved with continued injection, and production rates have held up well. Ultimate recovery from the pilot waterflood may therefore approximate the predicted ultimate recovery (fig. 10).

PRODUCTION-DECLINE ANALYSIS

Oil production from the Kane sand pilot waterflood has declined since April 1964. Various methods and mathematical relationships were investigated to evaluate this decline. Exponential, hyperbolic, and harmonic declines were utilized for fitting the production data.

Before analyzing the different types of decline curves, the following assumptions must first be made: (1) The production is at capacity; (2) the pressure is constant or proportional to the amount of remaining oil; and (3) the wells will produce under stabilized conditions, meaning the drainage area should have reached a maximum constant size. The various types of decline curves analyzed are as follows.

Exponential decline, also called semilog or constant-percentage decline, is characterized by the fact that the drop in production rate per unit of time is proportional to the production rate. The simplest method of recognizing exponential decline is the loss-ratio procedure (16), where the loss ratio is constant and defined as the production rate divided by the change in production rate per unit time.

The hyperbolic or log-log type of decline can be recognized when the difference of the loss ratios are constant or nearly so. Differences of consecutive initial values in the loss ratio is sometimes referred to as the b exponent (22), which can vary between 0 and 1. When b is 0 the curve is exponential, and when b has a value between 0 and 1 the curve is hyperbolic. There is also the special case when the b exponent equals 1. This is known as harmonic decline.

The theory of production decline curves is relatively simple, but fitting the production data to these mathematical techniques is considerably more difficult. For the Kane sand production, the calculated loss ratios were not constant nor could a constant difference of loss ratios, or b values, between 0 and 1 be found.

The inability to establish an exponent b indicates the inaccuracy of estimating from a short decline period (6); however, even more errors may exist in an oil reservoir that is being waterflooded. The Kane sand, as for most waterfloods, consisted of a period of fill-up and then a period during which the oil-production rate responded to water injection. After the peak oil-production rate was attained, the oil-production rate started to decline as the flood reached maturity. During this time, the water saturation and relative permeability to water increased while the oil saturation and relative permeability to oil decreased. The oil-production decline, however, may or may not be a direct function of time (18); although at all times it is a function of the volume of water injected. Therefore it should be emphasized that true decline for secondary waterfloods seldom exists because water injection, and thus oil production, is subject to the control of the operator (18).

Since the production decline for the Kane sand did not fit the standard techniques, an alternate method was used. Arps (1) calculated the range of

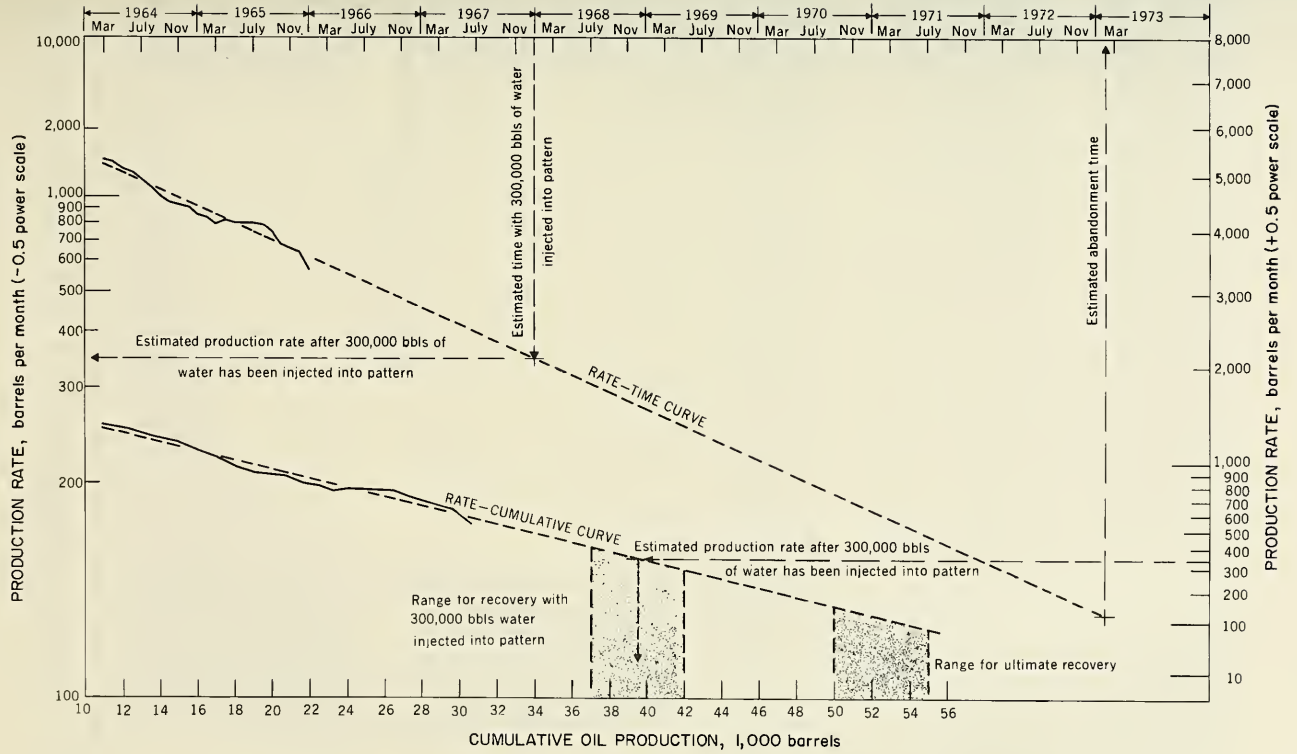

FIGURE 11. - Straight-Line Projection of Hyperbolic Decline (Exponent b = 0.5), Pilot Waterflood, Kane Oilfield, Elk County, Pa.

most b exponent values from data assembled by Cutler (11). According to these calculations, the value of the b exponent in the majority of cases appears to be between 0 and 0.5. A trial and error method (1) was then used on the Kane sand decline data. A b exponent of 0.5 was found to best approximate a straight line to the Kane sand production data. The hyperbolic-decline curve, as presented by Arps, was then derived. The results of this mathematical technique are shown graphically in figure 11.

As indicated, a recovery of 37,000 to 42,000 barrels of oil is expected if 300,000 barrels of water is injected into the pattern (this corresponds to about 675,000 barrels of cumulative water injected). If the flood is continued to a production rate of 1 barrel per day per well, an additional 13,000 barrels of oil may be produced, or a total of 50,000 to 55,000 barrels (129 to 142 barrels per acre-foot) may be recoverd. By using a similar economic limit and the prediction described earlier, an ultimate oil recovery of 45,000 barrels would be calculated.

Figure 11 can also be used to estimate the cumulative oil production at a particular time. Suppose, for example, that an estimate of cumulative oil production to January 1968 is needed. The first step is to estimate the production rate for that time from the rate-time curve using the scale on the left of figure 11. For January 1968, the rate indicated on the figure is an

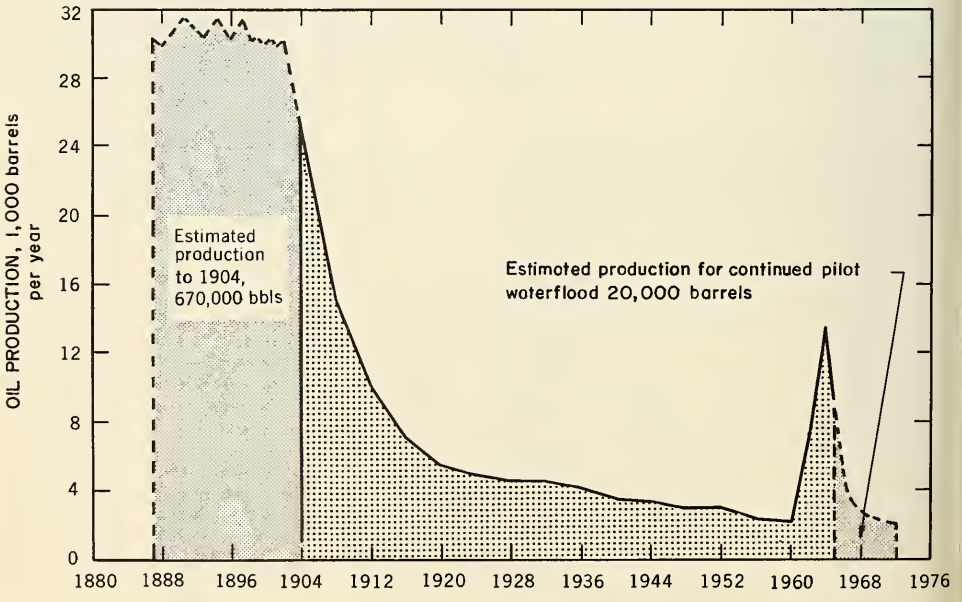

FIGURE 12. - Production History and Prediction of Future Performance, Pilot Waterflood, Kane Oilfield, Elk County, Pa.

estimated 350 barrels per month. This rate value is then transferred to the right-hand scale on the figure and extrapolated to the rate-cumulative curve. As shown, the predicted cumulative production for January 1968 is 39,500 barrels. Inherent in any estimate from this figure is the assumption that the operator will continue to inject water at about the current rate of 11,600 bbl per month.

Figure 12 illustrates the cumulative history of Kane sand oil production from Land Warrant 3777 in the Allegheny National Forest. Oil recovered through January 1966 by primary-recovery (2) and secondary-recovery methods is estimated to be 1,047,000 stock-tank barrels, and oil recovery from continued water injection into the pilot waterflood area should be an additional 20,000 barrels.

DISCUSSION OF RESULTS

The likelihood that communicating fractures existed in the formation was confirmed by the operator in August 1963 when fluorescein-dye tracers were injected. Further tracer work was initiated in January 1965 by the Bureau of Mines (8) to reconfirm that fractures or near-miss fractures existed in the Kane sand reservoir. It was also hoped that, if they did exist, the percentage of water going through the fractures could be determined.

The response of these later tracer tests was not very encouraging. A small amount of the tagged water was produced 4 days after the tracer was injected. Although this definitely confirmed that a fracture system did exist (8), the volume of tagged water produced did not materially change the water-injection calculations used in the prediction.

When the first tests were performed in 1963, water injection into the pattern had been underway for only a few months. At this time, a high differential pressure between injection and producing wells undoubtedly existed. The short time required to produce the injected dye in 1963 could not be duplicated in the January 1965 tests. Instead, considerably smaller amounts of tracer were produced over longer periods of time.

At the time the second series of tests was made, the waterflood had been in operation for more than 2 years. During that time, the high differential pressure which initially existed in the reservoir was no longer present, and this condition would have permitted the fractures to partially close.

During a third series of tracer tests conducted in August 1965 at still higher injection pressures, dye was produced in a short period of time which indicated greater fracture opening. The extent and fluid intake of the fractures in the pilot waterflood area is therefore a function of the existing differential pressure in the reservoir.

Another interesting effect of the fracture system is the preferential flow path of the injected water. All the successful tracer tests indicate that this flow is along a line north 76° to 79° east with reservoir flow occurring primarily from west to east.

In preparing a study of this nature, the various parameters inherent to the method are very difficult to establish. When viewing the predicted results for the pilot waterflood, it is quite evident that the originally assumed initial gas saturation of 20 percent was in error; whereas, a saturation of 13 percent may be more realistic.

The favorable field response of the pilot waterflood has prompted the operator to expand his present project. The addition of 180 acres southwest of the current pilot waterflood was initiated in January 1966, and will add approximately 10 normal five-spots to the existing waterflood pattern. Orientation of the fracture system will also be attempted in order to establish communication between injection wells and thus create a linear flow system. The knowledge gained in fracture extent and orientation from the current waterflood will, if successful, lead to a more efficient waterflood pattern in the Kane oilfield.

CONCLUSIONS

The assumed gas saturation of 20 percent used in the original prediction was incorrect. The maximum oil recovery predicted at the time the assumption was made is considerably less than the actual field performance. Furthermore, the field performance indicates that an initial gas saturation of 13 percent existed in the reservoir. When this gas saturation is used, predicted results for ultimate recovery agree with calculated values derived by decline-curve analysis. Based upon the latter calculations, the pilot waterflood in the Kane sand should ultimately produce 50,000 to 55,000 barrels of oil, or 129 to 142 barrels per acre-foot.

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APPENDIX. - PRODUCTION DATA AND CORE ANALYSES

TABLE A-1. - Production and injection data, Kane sand pilot waterflood, Kane oilfield, Land Warrant 3777, Highland Township, Elk County, Pa.

Month	Production							Injection	
	Oil			Water		Oil and water	Water-oil ratio	Monthly barrel	Cumulative, barrel
	Monthly, barrel	Daily, barrel per day	Cumulative, barrel	Daily, barrel per day	Cumulative, barrel	Cumulative, barrel			
					1962				
December	-	-	-	-	-	-	-	5,424	5,424
					1963				
January	-	-	-	-	-	-	-	4,864	10,288
February	-	-	-	-	-	-	-	18,560	28,848
March	-	-	-	-	-	-	-	19,934	48,782
April	239	21.1	239	-	-	239	0.0	19,630	68,412
May	471	15.2	710	1.2	37	747	.1	22,126	90,738
June	531	17.7	1,241	43.1	1,330	2,571	2.4	22,190	112,928
July	583	18.8	1,824	61.1	3,223	5,047	3.3	22,705	135,633
August	862	27.8	2,686	72.7	5,478	8,164	2.6	20,107	155,740
September	963	32.1	3,649	67.8	7,512	11,161	2.1	18,296	174,036
October	1,066	34.4	4,715	68.0	9,621	14,336	2.0	17,460	191,496
November	1,104	36.8	5,819	68.8	11,682	17,501	1.9	16,090	207,586
December	1,271	41.0	7,090	65.4	13,710	20,800	1.6	15,693	223,279
					1964				
January	1,243	40.1	8,333	67.1	15,790	24,123	1.7	15,590	238,869
February	1,262	43.5	9,595	74.7	17,957	27,552	1.7	13,847	252,716
March	1,395	45.0	10,990	81.4	20,479	31,469	1.8	14,791	267,507
April	1,362	45.4	12,352	86.2	23,063	35,415	1.9	13,591	281,098
May	1,283	41.4	13,635	73.5	25,986	39,621	2.3	14,626	295,724
June	1,161	38.7	14,796	116.5	29,463	44,259	3.0	14,370	310,094
July	1,206	38.9	16,002	123.9	33,304	49,306	3.2	15,061	325,155
August	1,048	33.8	17,050	122.4	37,098	54,148	3.6	15,120	340,275
September	943	31.4	17,993	138.4	41,250	59,243	4.4	15,210	355,485
October	967	31.2	18,960	136.7	45,492	64,452	4.4	14,594	370,079
November	900	30.0	19,860	134.0	49,512	69,372	4.5	13,779	383,858
December	886	28.6	20,746	133.2	53,641	74,387	4.7	14,159	398,017
					1965				
January	911	29.4	21,657	137.8	57,912	79,569	4.7	14,659	412,676
February	739	26.4	22,396	133.1	61,639	84,035	5.0	12,142	424,818
March	827	26.7	23,223	130.0	65,665	88,888	4.9	13,397	438,215
April	789	26.3	24,012	133.1	69,657	93,669	5.1	12,617	450,832
May	798	25.8	24,810	136.6	73,892	98,702	5.3	12,210	463,042
June	797	26.6	25,607	138.4	78,046	103,653	5.2	11,689	474,731
July	779	25.0	26,386	138.3	82,333	108,719	5.5	11,147	485,878
August	789	25.5	27,175	149.6	86,971	114,146	5.9	11,839	497,717
September	713	23.8	27,888	144.1	91,295	119,183	6.1	11,342	509,059
October	700	22.6	28,588	145.6	95,662	124,250	6.4	11,300	520,359
November	663	22.1	29,251	141.8	100,058	129,309	6.4	11,743	532,102
December	631	20.4	29,882	142.3	104,470	134,352	7.0	11,740	543,842
					1966				
January	540	17.3	30,422	133.5	108,609	139,031	7.7	11,626	555,468

TABLE A-2. - Core analysis based on lithologic description, Kane sand, well E-3, Kane oilfield, Land Warrant 3777, Highland Township, Elk County, Pa.

Sample	Permeability, md	Porosity, percent pore volume	Saturation percent pore volume		Oil content, barrel per acre-foot	Salt content, mg NaCl per gram core
			Oil	Water		
Lithologic section 1 - 4.9 feet of sandstone[1]						
1.....	8.6	13.4	24.0	1.0	250	-
2.....	4.7	12.5	23.2	7.3	226	1.17
3.....	3.4	12.9	18.7	11.3	188	1.13
4.....	4.5	12.8	29.8	5.9	297	-
5.....	7.4	13.4	45.0	1.1	470	-
6.....	6.1	12.6	32.4	4.2	319	-
7.....	16.4	15.0	24.2	4.1	283	1.00
8.....	10.3	14.4	21.5	4.2	242	-
9.....	6.9	13.1	25.5	6.6	261	.97
Average....	7.6	13.3	27.1	5.1	282	1.07
Lithologic section 2 - 8.5 feet of sandstone[2]						
10.....	0.4	8.8	25.9	25.2	179	-
11.....	.2	7.5	29.8	8.0	175	-
12.....	<.1	3.4	68.3	7.5	182	-
13.....	.3	5.7	30.5	32.0	137	-
14.....	<.1	1.7	-	-	-	-
15.....	<.1	3.4	-	-	-	-
16.....	1.2	9.6	24.7	13.5	184	.90
17.....	<.1	2.9	-	-	-	-
18.....	<.1	4.6	-	-	-	1.13
19.....	.4	6.1	31.1	41.9	149	-
20.....	.2	5.3	37.1	48.4	154	-
21.....	2.5	11.8	18.7	17.5	173	-
22.....	.5	6.9	15.5	47.8	84	-
23.....	1.0	6.8	29.7	33.8	158	-
24.....	.3	6.6	46.1	18.5	239	-
25.....	1.0	3.6	-	-	-	-
26.....	<.1	2.9	-	-	-	-
27.....	<.1	2.5	-	-	-	-
< Less than Average....	.5	5.6	32.5	26.7	165	1.02
Lithologic section 3 - 2.3 feet of sandstone[3]						
28.....	0.1	1.8	-	-	-	1.57
29.....	<.1	2.8	-	-	-	-
30.....	1.3	9.9	33.4	2.5	258	-
31.....	<.1	3.2	-	-	-	-
32.....	<.1	2.4	-	-	-	1.63
< Less than Average....	.3	4.0	33.4	2.5	258	1.60

See footnotes at end of table.

TABLE A-2. - Core analysis based on lithologic description, Kane sand, well E-3, Kane oilfield, Land Warrant 3777, Highland Township, Elk County, Pa.--Continued

Sample	Permeability, md	Porosity, percent pore volume	Saturation percent pore volume		Oil content, barrel per acre-foot	Salt content, mg NaCl per gram core
			Oil	Water		
Lithologic section 4 - 1.1 feet of sandstone[4]						
33.....	<0.1	1.0	-	-	-	1.47
34.....	<.1	.9	-	-	-	-
35.....	<.1	1.2	-	-	-	-
< Less than Average....	<.1	1.0	-	-	-	1.47
Lithologic section 5 - 3.6 feet of sandstone[5]						
36.....	0.1	2.7	-	-	-	1.27
37.....	.1	.5	-	-	-	-
38.....	.8	.9	-	-	-	1.77
39.....	.4	3.8	-	-	-	-
< Less than Average....	.4	2.0	-	-	-	1.52
Lithologic section 6 - 3.3 feet of sandstone[6]						
40.....	<0.1	1.0	-	-	-	-
41.....	<.1	3.0	-	-	-	1.33
42.....	<.1	2.3	-	-	-	2.43
43.....	.3	.9	-	-	-	-
< Less than Average	.1	1.8	-	-	-	1.88

Average Results

Lithologic section	Core recovered, feet	Permeability, md	Porosity, percent pore volume	Saturation percent, pore volume		Oil content, bbl per acre-foot	Salt content, mg NaCl gram per core
				Oil	Water		
1.....	4.9	7.6	13.3	27.1	5.1	282	1.07
2.....	8.5	.5	5.6	32.5	26.7	165	1.02
3.....	2.3	.3	4.0	33.4	2.5	258	1.60
4.....	1.1	<.1	1.0	-	-	-	1.47
5.....	3.6	.4	2.0	-	-	-	1.52
6.....	3.3	.1	1.8	-	-	-	1.88

[1]Medium brownish gray, mostly very fine-grained, highly angular, tightly cemented, very slightly calcareous; oil stain.

[2]Medium light to medium gray, very fine- to fine-grained, highly angular, slightly calcareous, tightly cemented, slightly micaceous, argillaceous; some shale partings.

[3]Medium brownish gray, very fine- to fine-grained, highly angular, tightly cemented, moderately to highly calcareous, micaceous, fossiliferous, argillaceous; some shale partings.

[4]Light gray, quartzitic, streaks of argillaceous and micaceous material, highly calcareous; fossiliferous.

[5]Medius gray, slightly calcareous, argillaceous; fossiliferous.

[6]Medium gray, silty; slightly micaceous.

TABLE A-3. - Core-analysis results, Kane sand, well E-1, Kane oilfield, Land Warrant 3777, Highland Township, Elk County, Pa.

Sample	Depth, feet	Sand thickness, total feet	Horizontal air permeability, md	Porosity, percent	Saturation, percent pore volume		
					Oil	Water	Gas
1	2,314.4	0.3	0.2	-	-	-	-
2	2,315.0	.4	.1	4.2	45.8	26.5	27.7
3	2,315.5	.2	1.0	-	-	-	-
4	2,316.0	.4	1.5	8.6	36.6	17.4	46.0
5	2,316.4	.4	.1	-	-	-	-
6	2,317.3	.5	3.4	11.9	27.8	25.9	46.3
7	2,317.8	.5	.9	-	-	-	-
8	2,319.2	.2	1.5	-	-	-	-
9	2,319.6	.2	.1	-	-	-	-
10	2,320.2	.4	.2	11.3	32.2	25.7	42.1
11	2,320.6	.3	.1	-	-	-	-
12	[1]2,323.7	.4	1.4	7.4	41.1	19.4	39.5
13	2,324.3	.2	1.6	-	-	-	-
14	2,325.0	.2	.1	-	-	-	-
15	2,325.9	.5	3.8	9.7	37.6	26.5	35.9
16	2,326.4	.5	8.5	-	-	-	-
17	2,326.9	.5	9.6	13.4	35.8	50.3	13.9
18	2,328.0	.5	6.5	13.7	30.5	38.5	31.0
19	2,328.5	.2	6.5	-	-	-	-
20	2,329.3	.3	.8	-	-	-	-
21	2,330.5	.5	4.6	11.2	33.2	24.8	42.0
22	2,331.3	.4	1.2	10.2	29.8	21.5	48.7
23	2,331.8	.2	.2	-	-	-	-
24	2,332.4	.4	9.4	10.9	29.1	31.3	39.6
25	2,333.5	.3	2.5	-	-	-	-
26	2,334.3	.6	2.5	10.4	26.8	20.6	52.6
27	2,337.2	.5	.6	6.1	26.2	21.4	52.4
28	2,339.1	.2	.3	7.4	28.9	22.9	48.2
29	2,339.5	.2	1.1	-	-	-	-
30	2,339.9	.2	1.4	10.2	23.9	10.1	66.0
31	2,341.3	.2	1.0	9.5	19.0	18.3	62.7
32	2,341.9	.4	4.6	10.6	30.8	24.2	44.8
33	2,343.0	.4	6.2	10.8	24.1	31.9	44.0
34	2,349.0	.6	3.1	10.8	23.2	57.1	19.7
34	2,349.6	.5	5.2	-	-	-	-
36	2,350.2	.5	.4	10.0	26.4	58.0	15.6
Average	-	-	2.6	9.9	30.4	28.6	51.0

[1]2.2 feet of core unrecovered.

EVALUATION OF A BATTERY-POWERED VEHICLE

By W. P. Haynes and H. B. Neilson

* * * * * * * * * * * * report of investigations 6918

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Stewart L. Udall, Secretary

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EVALUATION OF A BATTERY-POWERED VEHICLE

by

W. P. Haynes[1] and H. B. Neilson[2]

ABSTRACT

To evaluate the potential use of battery-powered vehicles, the Bureau of Mines studied the performance of a battery-powered truck propelled by a 9.6 kw dc motor in considerable detail under various driving conditions. Some of the factors investigated were: Gear ratios, payload (1,468 lb maximum), road grade, stops made per mile, and charging time. With the exception of some difficulty with brush wear, operation and maintenance of the truck was generally trouble-free.

On range tests carrying an 868-lb payload a distance of about 50 miles at an average speed of about 19 mph in normal driving, the Bureau's battery-powered truck averaged 1.6 to 1.9 miles per ac kwhr input. Stop-and-go tests indicated that prospects for the use of battery-powered trucks in house delivery service within city limits are good; performance of the Bureau truck was sufficiently high for that type of service. The estimated power cost of 2.65 cents per mile while making 10 stops per mile was attractively low from the standpoint of fuel costs.

INTRODUCTION

The progressive development of more compact electric motors, more efficient storage batteries, and lighter and stronger materials of construction has provided incentive for further improvement of battery-powered vehicles for on-the-road use. From the standpoint of national resources, any large-scale road use of battery-powered vehicles would increase the demand for electricity, and hence for utilization of our more abundant mineral fuels. The Bureau of Mines has therefore been interested in obtaining data on the performance and potential energy requirements of battery-powered vehicles.

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Work on manuscript completed May 1966.

FIGURE 1. - Bureau of Mines Electric Truck (12.9 Brake Horsepower).

To provide a reference for evaluating future developments in this field, the Bureau has conducted performance tests on a commercially available battery-powered truck. The results of this limited study are presented in this report. The data obtained include measurements of the energy used, truck speed, and range under various road and driving conditions. Maintenance requirements were also studied.

ACKNOWLEDGMENTS

Design and installation of the instrumentation was provided by Paul L. Golden, mechanical engineer, and Ralph E. Boyce, engineering technician. During the initial stages of the project, Robert J. Leister, chemical engineering technician, was the project assistant, responsible for calibrating instruments and the setting up of operating procedures. All are with the Bureau of Mines, Bruceton, Pa.

DESCRIPTION OF EQUIPMENT

Truck

The body of the test truck was constructed of fiber glass and steel. An exterior view of the truck is shown in figure 1. General specifications and dimensions of the truck are given in table 1. The empty truck weight of 4,670 lb, at zero payload, excludes the weight of the driver and the instruments installed by the Bureau. The nameplate rating of the motor is equal to 12.9 brake horsepower or 9.6 kw. Electric power was supplied by an industrial motive battery that had a plastic case, plastic cell partitions, and porous sheaths of plastic and fiber glass to retain the active material on the tubular elements. The motive battery was comprised of two units. One unit was mounted on each side of the truck on plastic-coated supports. The battery supports rolled out to permit easy inspection and maintenance of the two units of the battery. The two halves of the motive battery could be connected either in series or in parallel, depending upon the setting of the motor controller. No regenerative braking system was provided for recharging the batteries on steep downgrades.

TABLE 1. - General description of the electric truck

Truck body:	
Allowable payload	1,500 lb
Empty weight, with batteries	4,670 lb
Body capacity	175 cu ft (approx.)
Wheel base	69 in
Rear door	45 inch height, 34 inch width
Turning radius	6-1/2 ft
Rear axle ratio	5.38:1
Gearbox ratios (nominal)	1:1; 1.85:1; 3.15:1; 4.15:1
Brakes	Service: 4-wheel hydraulic Parking: Mechanical, on shaft
Tire size	670.15-6 ply
Truck speed (Maximum cruising)	30 mph on level grade A or B roads
Drive motor	Direct current, series wound; continuous duty 2,450 rpm; 120 amp; 80 volts; 90° C windings; 105° C commutator
Motive battery	Lead-acid, 36 cell, 11 plates per cell; discharge capacity 275 amp hr in 6 hr; 290 amp hr in 8 hr; limiting rate of charge at finish 15 amp; 2,200 lb (approximate weight).
Battery charger	Self-regulated, automatic; 220 volt, single phase, 60 cycle input; 40 amp dc maximum output, 8 to 10 hr recharge cycle.
Accessories battery	Lead-acid, 12 volt

A manually operated gear shift was used to change the truck speed. The truck had no clutch, so the driver had to anticipate road conditions and shift into the proper gear while the vehicle was stopped. The transmission train had a limited slip axle to furnish dual traction on icy roads.

Other features originally furnished with the truck included an automatic air-blower system to ventilate and cool the truck motor, a thermal overload switch which protected the motor from extended periods of current overload, an odometer, and a speedometer. An amp hr meter served as a fuel gage and enabled the driver to estimate the distance the truck could travel before the battery needed charging.

Motor Controller

A schematic wiring diagram of the motor and its control system is shown in figure 2. Referring to figure 2, the sequence of operation of the electric motor and its controls was as follows:

(1) The key switch was turned on to make control power available.

(2) The direction of travel was selected by operating the forward-reverse selector switch. This closed directional contactors (F) or (R) across the armature. When the handbrake switch was released these contactors closed and remained closed until either the key switch or the footbrake switch was opened.

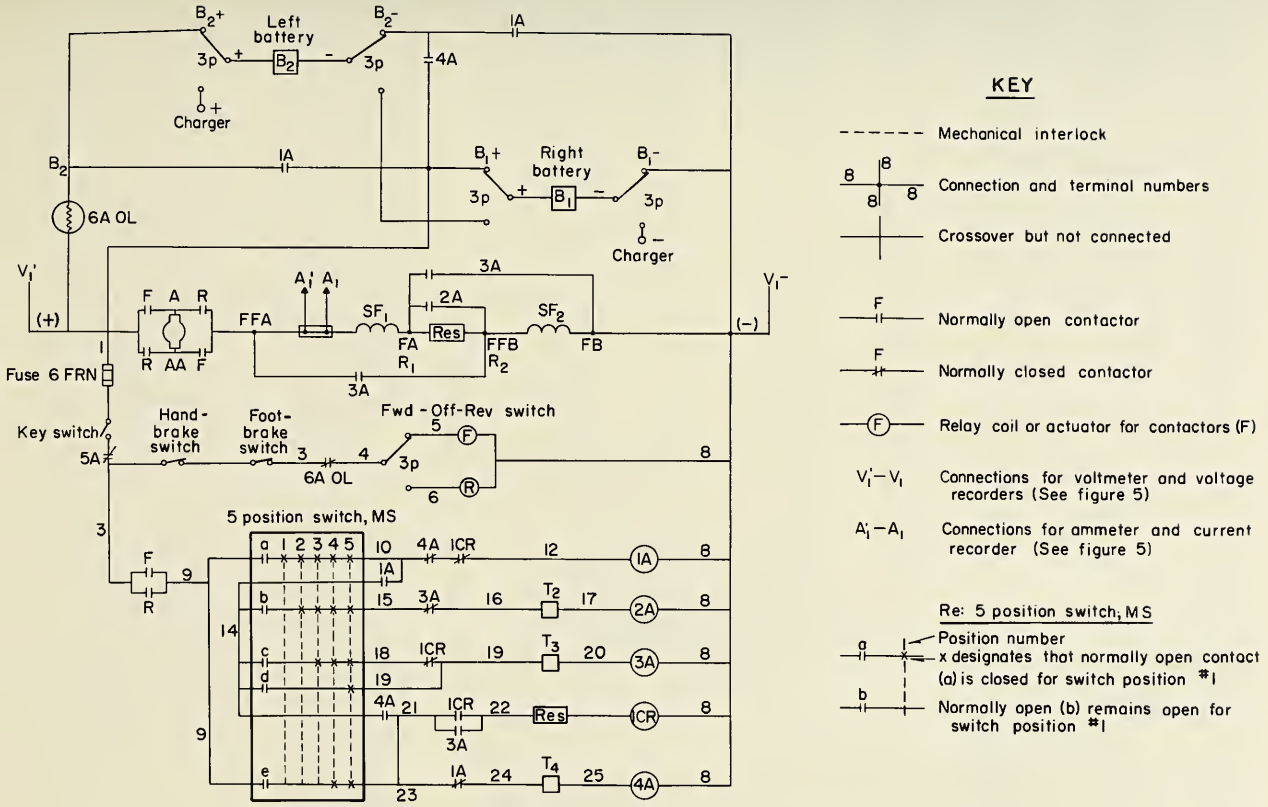
(3) Speed was controlled by a 5-position, foot-operated switch (MS), as follows:

(a) Depressing the pedal of switch (MS) to the first position (1), closed contactor (a) and energized relay coil (1A) to put the batteries in parallel. Acceleration occurred with the motor fields (SF_1 and SF_2) and the resistor in series.

(b) Depressing the pedal to position (2) closed contactor (b) and energized timer (T_2) which energized relay coil (2A) after a time delay. The batteries remained in parallel, and the motor fields in series; but the field resistor shorted out. The motor continued to accelerate.

(c) Depressing the pedal to position (3) energized timer (T_3) which actuated contactor (3A) after a time delay. The batteries remained in parallel. The motor fields switched to parallel and (2A) contactor was opened, reinserting the series field resistor (2A). Auxiliary interlock (3A) was closed to set up the circuit for the (1CR) relay.

(d) Depressing the pedal to position (4) closed contactor (e) and thereby closed the (1CR) relay circuit through interlocking contactor (3A). Relay (1CR) was energized and remained energized through its own contactor. Energizing relay (1CR) also deenergizes relays (1A), (3A), and (2A). Deenergizing of relay (1A) closed contactor (1A) in the (4A) relay circuit. After a time delay due to timer (T_4), the energized (4A) relay put the batteries in



KEY

- Mechanical interlock
- Connection and terminal numbers
- Crossover but not connected
- F — Normally open contactor
- F — Normally closed contactor
- (F) — Relay coil or actuator for contactors (F)
- $V_1'-V_1$ — Connections for voltmeter and voltage recorders (See figure 5)
- $A_1'-A_1$ — Connections for ammeter and current recorder (See figure 5)

Re: 5 position switch, MS

- a — Position number; x designates that normally open contact (a) is closed for switch position #1
- b — Normally open (b) remains open for switch position #1

FIGURE 2. - Schematic Wiring Diagram of the Motor and Motor Control System.

series, and reenergized terminal 14 in switch (MS) which reenergized relay (2A) to short circuit the resistor in the series field.

(e) Depressing the pedal to position (5) finally closed contactor (d) and energized timer (T_3). After a time delay, relay (3A) was actuated to put the series fields in parallel. Relay (2A) was deenergized to utilize the series resistor as a low-grade insulator.

(4) The motor control was so designed and interlocked that the operator could depress the pedal switch (MS) to any one of the five positions, and controlled sequence acceleration would take place up to the position held on the (MS) switch.

(5) The (F) and (R) contactors were mechanically interlocked to assure that only one or the other could be closed. This also applied to the battery contactors (1A) and (4A).

(6) In case of an overload on the motor, a thermal relay (6A, OL) was provided which could open up the (F) or (R) circuit and cut off traction power. The overload relay could be set for automatic reset which, after a time delay, allowed the contactors to reclose and the traction power to be reapplied.

Due to the location of shunt A_1'-A_1 which supplied the current signal to the current recorder, only the field current that passed through field coil SF_1 was measured. Thus, when the field coils of the motor were in series (corresponding to foot switch positions 1, 2, and 4), the recorder measured full motor current; but when the field coils were in parallel (switch positions 3 and 5), the recorder only measured one-half motor current. Except for short periods of starting and stopping, the foot switch was always in position 5 for normal driving; thus the current recorder was generally measuring one-half motor current.

Battery Charger

The motive battery charger was an automatic self-regulated charger which was mounted in the rear of the truck. The charging current or charge rate of the motive battery charger was controlled by a balanced transformer and saturable reactor combination which used the battery voltage as a reference. (See wiring diagram of charger, figure 3.) Since the motive battery itself was used as a reference, its own voltage became the primary control of the charge rate.

The manufacturer's explanation of the operation of the charger follows: "When a battery is discharged or standing idle its terminal voltage has a tendency to seek 2.1 volts/cell. Upon recharging the battery, the charger tends to go out to its maximum charge and is limited only by the battery voltage. As the battery voltage increases, the charging current decreases due to the saturable reactor sensing circuit. If the battery is heavily discharged, the charge rate is high and decreases slowly. If the battery is only partially discharged, the battery voltage rises rapidly and the charging current decreases rapidly until the battery reaches 2.5 volts/cell which shuts the

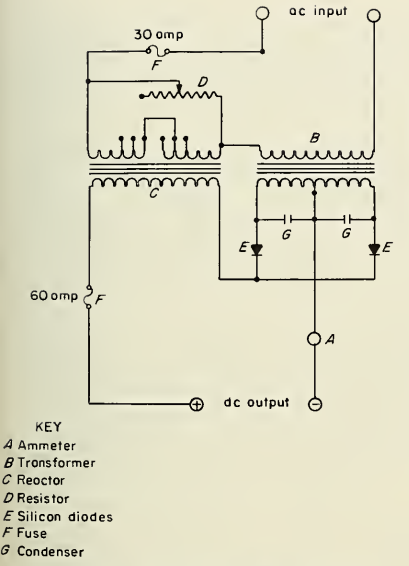


FIGURE 3. - Wiring Diagram of Automatic Battery Charger.

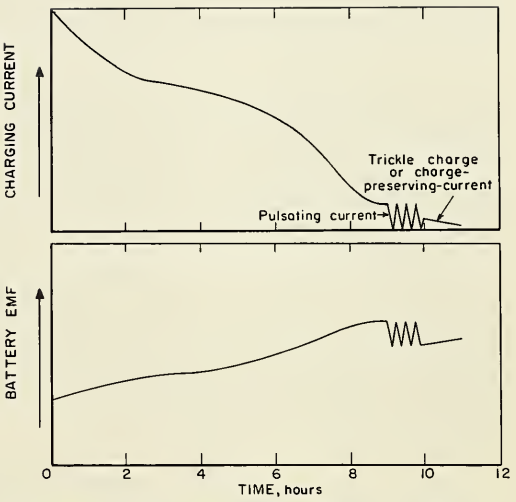


FIGURE 4. - Typical Charge Curve for Automatic Battery Charger.

charging current to a trickle charge-preserving-charge." An illustration of a typical charging curve is shown in figure 4.

"It is necessary to trickle charge the battery at a very low rate in order to keep the battery fully charged. Therefore, after the charger has brought the battery to full charge it shuts down to a small charge-preserving-charge to maintain the battery at full charge until disconnected.

"The charger has three basic components: Transformer, saturable reactor or control unit, and silicon rectifying stack. The basic operation of these components is as follows: When a discharged battery is connected across the dc output terminals of the charger, the battery voltage, being lower than the charger terminal voltage, causes a dc output current flow from the charger to the battery. This current flows through the center coil of the reactor, which is connected in series with the dc output, and causes the reactor to begin to saturate. As a result of this saturation, the ac voltage across the side legs of the reactor is shifted to the primary of the transformer which induces a higher secondary voltage. The input voltage to the stack increases and in turn increases the rectified output voltage to raise the charge rate. If the battery is completely discharged, the dc output continues to increase until the reactor is completely saturated, causing the maximum output current.

"As the battery charges and its voltage increases, the charging current decreases, causing de-saturation of the reactor which allows the voltage to

begin shifting from the transformer to the reactor, which in turn decreases the charge rate. This cycle continues until the on-charge battery voltage reaches 2.5 volts/cell which will allow only a trickle charge-preserving-charge rate to continue in order to keep the battery fully charged.

"When the charger has brought the battery to full charge and the charge rate decreases to about 10 percent, the charger shuts down to a trickle. If this small trickle is not enough current to hold the battery voltage up, the charger will kick out on its charge curve, and bring the battery voltage up again and then shut down. These oscillations or pulsations continue until the battery is charged sufficiently to maintain its voltage with only a small charge-preserving-charge.

"This infinite step method of charging allows the battery to convert electric energy to chemical energy without forcing the conversion, which in turn reduces battery temperatures and excessive gassing. Since the agitation of the electrolyte is somewhat restricted, the specific gravity reading of an unagitated battery at the end of a fast charge may read lower (1.240-1.260) because the electrolyte taken from the surface of the battery may not be thoroughly mixed."

Instrumentation

The principal electrical instruments used for gathering test data are shown on the instrumentation diagram in figure 5 as follows: Two kilowatt-hour meters for measuring energy input to the motive battery charger and to the motive battery; two millivolt recorders, which recorded the current and voltage to either the motor or to the charger output; and one millivolt recorder for recording the vehicle speed as measured by a tachometer generator. (Refer to figure 6 for the tachometer generator circuit.) Accuracies of the millivolt recorders were within 1/2 percent of full scale. Distance marks in units of 100 and 1,000 feet traveled were superimposed on the speed curve. Pulse signals to the distance marker were transmitted from a counter system which was driven by the transmission shaft.

While the vehicle was on the road, the 12-volt service battery and a converter (fig. 5) supplied the 110-volt ac power to the three recorders, as well as to the automotive accessories. The following accessories were powered by the 12-volt service battery, but are not shown in figure 5: Headlights, taillights, stoplight, domelight, turn signal, wipers, and the motor cooler fans. Also not shown in figure 5 are an ampere-hour meter, a dc ammeter to measure the charging current, and a dc ammeter located on the dashboard to enable the driver to check the motor current.

A 3-plug gang connector connected the 220- and 110-volt dc power supply to the truck for charging the batteries. As shown by figure 5, the recorders could be powered directly from the ac power supply, while the 12-volt service battery was being charged. A gang plug alarm relay was provided to break the key switch circuit to prevent the truck from being operated before the 3-plug gang connector was disconnected.

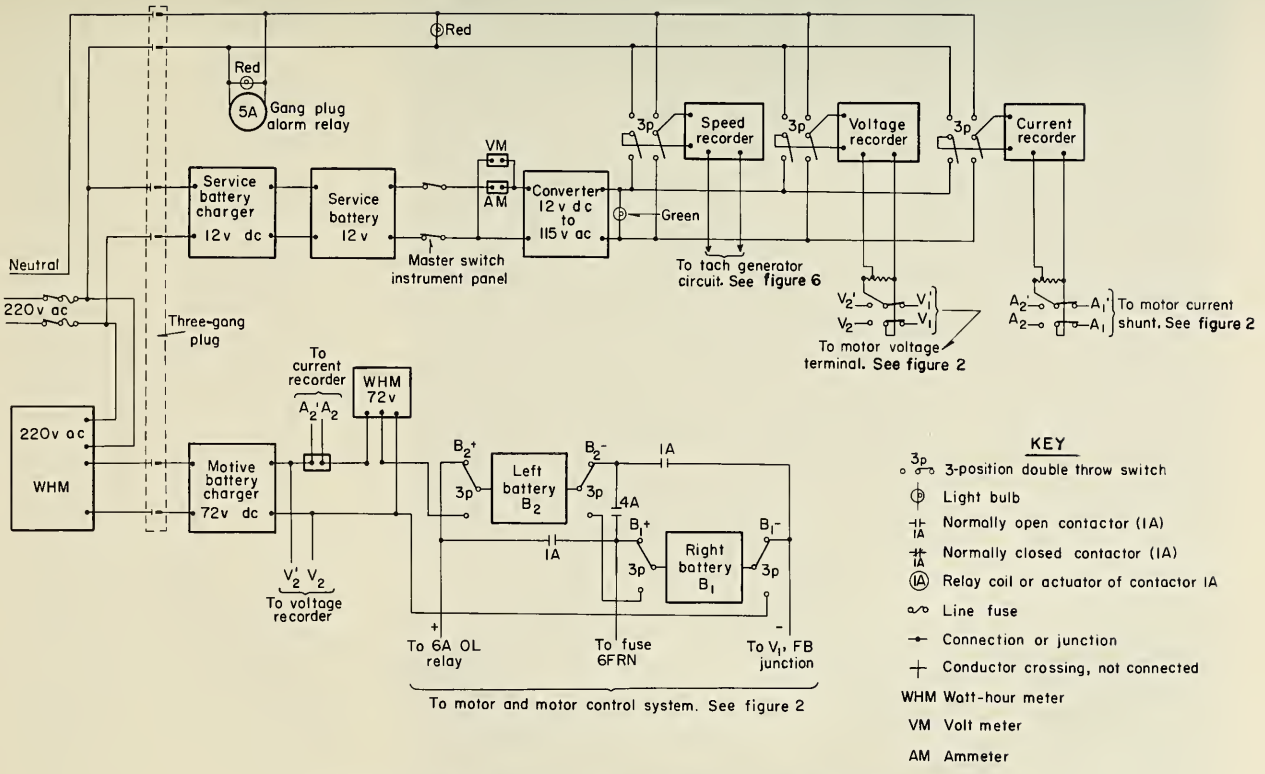


FIGURE 5. - Wiring Diagram of Instrumentation of Electric Vehicle.

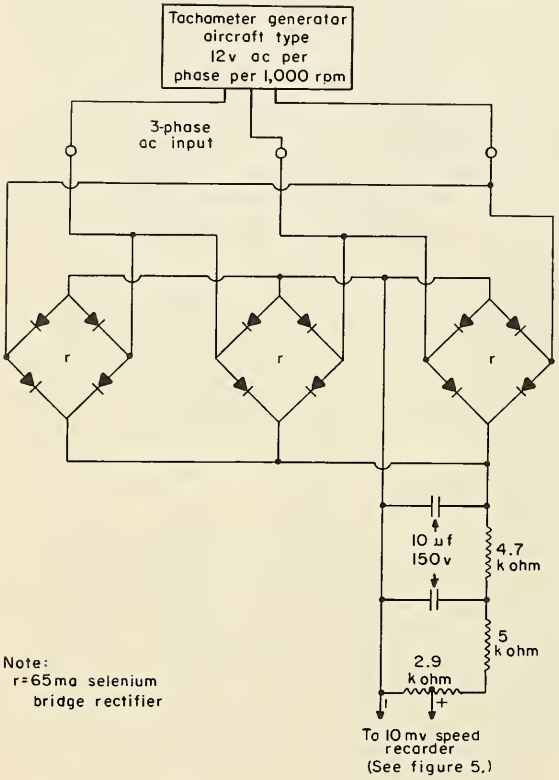


FIGURE 6. - Tachometer Generator System.

As further indicated in figure 5, the load on the 12-volt service battery could be determined from voltmeter and ammeter readings.

A U-tube mercury inclinometer was installed in the truck. It had an effective horizontal length of 50 inches, and vertical subdivisions of 0.05 inch, allowing measurement of road grades to within 0.1 percent precision.

Figure 7 is a view of the interior of the truck showing part of the instrumentation. The use of tennis balls to cushion the instrument panel from road shocks can be seen in the photo.

GENERAL OPERATIONS

Objectives

Operation of the truck was divided into two categories: General tests or operations, and controlled experiments. Studies of operating variables were conducted in the controlled experiments. Operation of the truck for any purpose other than a controlled experiment was considered as a general operation or test.

Some of the objectives of general operation were to accumulate mileage and operating time, to keep the battery in an activated state, and to calibrate the instrumentation. Principal topics of interest in the general tests were: Battery activation, the general handling of the truck, the practical range of the truck, and the recording of basic performance characteristics of the truck during typical operations.

General Procedure

The general experimental procedure consisted of driving the truck over the desired route under the desired conditions, logging the procedures and events, and collecting the necessary operating data. Whenever possible, a complete trip was made each workday with sufficient use of the battery to

FIGURE 7. - Instrument Panel Inside the Electric Truck.

require an overnight charging of the battery. Basic data covering charging operations, driving conditions, and trip data were collected for each trip. Occasionally, graphic recordings were made of the truck speed, distance traveled, motor current, and voltage.

Standard Courses and Test Sections

Since initial operations of the truck were concerned mainly with getting the battery activated and to accumulate mileage, standard courses and test sections were not used until the 67th trip. Two standard courses were laid out to reduce scatter in the operating data. Standard course No. 1 comprised two separate routes which totaled a distance of 34.3 miles. Course No. 2 consisted of two trips over a 13.7-mile route for a total of 27.4 miles. All roads were either concrete or asphalt macadam. Six test sections having

different road grades were located within the two standard courses. The road grades in percents for test sections 1 through 6, respectively, are 9.66, 8.09, 5.60, 3.40, 2.37, and 0.82.

Calibrations

The kilowatt-hour meters were adjusted and calibrated by the manufacturer to have a percent registration[3] of 99.5 to 100.1 percent at various loads. For the first 140 trips, the dc kilowatt-hour meter was mounted in the truck. Road vibrations caused the average percent registration of the dc kilowatt-hour meter to decline to about 97 percent. After trip 140, the dc kilowatt-hour meter was removed from the truck, reconditioned, recalibrated, and then remounted on the wall of the garage alongside the ac watt-hour meter, instead of in the truck, to maintain its initial calibration. After test 140, the average percent registration for both the ac and dc kilowatt-hour meters for most of the battery chargings was about 99.9 percent.

Readings of the dc kilowatt-hour meter and of the ampere-hour meter were also checked against the reference of dc kilowatt-hours and ampere-hours as determined by integration of the voltage and amperage charts. Prior to test 140, the dc kilowatt-hour meter reading values were 4 to 6 percent lower than the dc kilowatt-hours determined by chart integration. After test 140, the reconditioned dc kilowatt-hour meter agreed within 1 percent of the dc kilowatt-hours determined by chart integration. Ampere-hour readings were about 6 percent lower than chart integrations for the low pulsating charging currents, and about 2 percent lower for the higher charging currents. Except when specifically noted otherwise in this report, all kilowatt-hour and ampere-hour meter readings are reported as uncorrected.

Specific gravity readings of the battery acid were determined within ± 0.001 unit with a hydrometer. After the battery temperature was taken into account, all specific gravity readings were adjusted to the values corresponding to the reference temperature of 77° F.

Effective diameters of the tires were determined at various tire pressures by rolling the truck over a 200-foot test section and counting the number of revolutions of the wheel. The average effective diameter of the tires, within ± 0.0008 foot, follows:

Tire pressure, psig:	Average tire diameter, ft
40	2.2145
50	2.2264
60	2.2299

Since the distance marker system was linked to the drive shaft of the truck, the precision of the distance marker was the same as that of the effective tire diameters.

---

[3] Percent registration = $\frac{\text{Kilowatt-hours registered}}{\text{Actual kilowatt-hours}} \times 100$.

The average deviation of measurements from the calibration curve for the speed recorder was ± 2.0 percent. The truck velocity was determined from measurements of the distance marker and time measurements of the chart drive. The recorder system required a 15-minute warmup period before consistent time readings were obtained on the chart.

Precision of Data

Estimates of standard deviations (s) of observations from their means are presented in many of the tables. Values of (s) generally range between 2 to 6 percent of means. This indicates good reproducibility of results. Furthermore, F tests at the 5-percent significance level indicate no significant differences in the variability of parameters. Nearly all inferences were statistically sound at the 20-percent level; frequently some were sound at the 5-percent level.

Basic Data

Log Book Data

Information on the course of events during the project was logged daily. A summary of the log showing major events and operations in chronological order, and overall truck performance follows.

July 3, 1961

Truck was received.

July 3-November 7, 1961 (trip numbers 1 to 6)

A 220-volt ac outlet and watt-hour meter were installed in the garage for charging the truck battery.

While awaiting the installation of recording instruments, orienting trips were made to activate the battery, to accrue mileage, and to check and adjust the accessories in the truck.

A test trip determined that the truck was too slow for use in the regular messenger service between the Pittsburgh and Bruceton Bureau stations as originally intended. The odometer mileage advanced from 0 to 235.

November 8, 1961

During trip 7 at 251 odometer miles, abrasion of the armature caused a short circuit in the motor.

November 9, 1961-January 16, 1962

Motor underwent repair at the factory. Calibration and installation of recording instruments continued.

January 17-January 29, 1962

The repaired motor was installed and tested.

January 29-November 28, 1962 (trip numbers 8 to 148)

General operation of the truck was resumed. Standard courses were established. Standard performance tests and studies of operating variables were conducted. The odometer mileage advanced from 253 to 5,089 miles.

November 29, 1962

On trip number 149 at 5,133 miles odometer reading, fragments from a worn commutator brush damaged the commutator surface.

November 30, 1962-March 14, 1963 (trip numbers 150 to 170)

The motor was repaired and installed. Many attempts were made to overcome an exceedingly high rate of brush wear. The odometer advanced from 5,133 to 5,684 miles.

March 15-June 28, 1963 (trip numbers 171 to 241)

Performance tests and variable studies were continued until the project terminated on June 28, 1963. Final odometer reading was 7,724 miles.

For the overall period of operation (totaling 241 trips and a corresponding 241 battery charges), the total kilowatt-hours ac input was 5,083, while the total kilowatt-hours dc charged into the motive battery was 3,808. This amounts to 75-percent efficiency for the battery charger. Other performance averages for overall operation during the entire project are:

Average number of miles traveled per trip	32.7
Average ampere-hour dc used per trip	178
Average miles traveled per kilowatt-hour, ac	1.53
Average miles traveled per ampere-hour, dc	0.181
Tire wear	1/16 inch/1,000 miles

Trip Data

An example of the trip data gathered on these tests is presented in table 2 which covers trips 36 through 46. Most of the trip data given in table 2 are self-explanatory. The start and end of each running period are expressed in naval time. Total running time for each trip excludes nonoperating periods that exceeded 10 minutes. Extensive rest periods are recorded under recuperation time. The weather conditions recorded are those that predominated during each trip. The automatic fans referred to in table 2 under "Remarks" (trips 36 and 37) were used to cool the motor, and were actuated by a thermally controlled switch located in the motor field. The fan circuit is not shown in the instrumentation wiring diagram. "No overload" means that the motor was not overloaded to the extent of opening the overload relay circuit. As also indicated under "Remarks," part of trips 39, 40, and 42 include running with the rear wheels suspended from the ground while calibrating the speed recorder.

TABLE 2. - Typical trip data, trips 36 through 46

Trip No.	Date and running time	Total running time, min	Recuperation time, min	Final odometer reading	Total miles traveled	Payload with driver, lb	Weather conditions	Temperature, ° F	Tire pressure, psig	Main routes traveled	Remarks
36	3/29/62 1005-1137; 1233-1328	147	56	1,115.0	41.0	820	Fair	71	60	Corrigan Dr. and E. Park Dr.	Automatic fan to motor came on three times; no overload kickout.
37	3/30/62 1019-1138; 1234-1333	138	56	1,154.8	39.8	820	Light rain	56	60	Corrigan Dr.	Motor fans came on once; no overload.
38	4/2/62 1255-1508	133	0	1,194.2	39.4	820	Cloudy	40	60	Corrigan Dr.	-
39	4/3/62 1340-1540	120	0	1,239.3	35.5	820	Cloudy	44	60	Corrigan Dr.	Put on 9.6 miles making speedometer calibrations with rear wheel jacked up.
40	4/5/62 0816-1022	126	0	1,277.3	38.0	820	Fair	47	60	Corrigan Dr.	Put on 8 miles running tests on hoist.
41	4/9/62 0832-1016; 1256-1339	147	160	1,323.5	38.3	820	Light rain	49	60	Corrigan Dr.	-
42	4/11/62 1255-1505	130	0	1,390.2	35.9	820	Light rain	46	60	Corrigan Dr.	31 miles on hoist before trip.
43	4/12/62 1002-1128; 1252-1342	136	84	1,427.8	37.6	820	Rain	43	60	Corrigan Dr. and E. Park Dr.	Heavy rain throughout the trip.
44	4/13/62 1245-1500	135	0	1,467.3	39.5	820	Very light snow	38	60	Corrigan Dr. and E. Park Dr.	Roads slightly wet.
45	4/16/62 0859-1017	78	0	1,489.8	22.5	820	Fair	35	60	Corrigan Dr.	Trip incomplete.
46	4/17/62 1256-1516	140	0	1,532.4	42.6	820	Cloudy	49	60	Corrigan Dr. and E. Park Dr.	-
Total	-	23.83 hr	5.93 hr	-	410.1	9,020	-	-	-	-	-
Averages	-	2.17 hr	-	-	37.3	820	-	-	-	-	-

Charging Data

Typical data on the charging of the motive battery for trips 36 through 42 are presented in table 3. The charge following a trip was arbitrarily assigned to that trip with a number identical to the trip number.

As indicated in table 3, the specific gravity, temperature, and acid level of the battery were tested at the start and end of each charging period. These readings usually were taken at the pilot cell. A different cell was selected as the pilot cell after about 10 charges. Specific gravity readings taken at ambient temperature were corrected to the equivalent specific gravity at 77° F. Increases in cell temperature of up to 8° F were frequently noted upon completion of a charge. Acid level in the battery was maintained to within 1/4 inch of the filler hole by adding distilled water as needed. The average increase in specific gravity during a charge is from 1.164 to 1.271 which gives an average net increase of 107 points per charge.[4]

As indicated in figure 2, the motive battery consists of a left and a right battery. As shown in table 3, the voltage of the left battery was higher than that of the right battery by 0.1 volt. When No. 2 and 3 taps were used on the charger, the average charging voltage across the left battery at the start of a charge was 36.6 volts of 2.03 volts per cell, and at the end of a charge, 40.3 volts or 2.24 volts per cell; thus the average increase in charging voltage was 0.194 volt per cell. Similarly, the open circuit voltage of the left battery increased from 35.0 volts or 1.94 volts per cell, to 39.6 volts or 2.20 volts per cell for a net increase of 0.26 volt per cell for an average charge.

The dc charging current is about 28 amperes at the start. At the finish, the current either oscillates between 2 to 8 amperes or remains constant at about 2 amperes.

Average inputs per charge for charges 36 through 42 as presented in table 3 are: 197 ampere-hours, 23.2 ac kilowatt-hours, and 18.0 dc kilowatt-hours. The kilowatt-hour values indicate that an energy loss of 22.4 percent occurs in the charger.

During charging of the truck's motive battery, the battery showed all of the known basic characteristics of a lead-acid battery. The dc charging voltage and amperage to the motive battery were recorded during the full 16-hour period of charge No. 121. Hourly readings were taken of the ac and dc kilowatt-hour meters, the ampere-hour meter, and the specific gravity of the battery acid. These charging variables are presented graphically as a function of charging time in figure 8. Figure 9 accurately shows three expanded portions of the voltage and amperage curves for the pulsating period of charge between the 10th and 16th hours.

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[4] 1,000 points equals a specific gravity of 1.000.

TABLE 3. - Charging of motive batteries, charges 36 through 42

Time	Date	Hours of charge	Start and end	Charge No.	Pilot cell No.	Cell temperature, ° F	Cell sp gr, 8 inches down	Specific gravity corrected to 77° F	Cell level from filler hole, inch	Meter reading, amp hr	Meter reading, ac kwhr	ac kwhr used
1530	3/29/62	-	Start	36	19	86	1.158	1.161	1/4	200	0835.8	-
0830	3/30/62	17	End	36	19	89	1.272	1.276	1/4	0	0860.0	24.2
1530	3/30/62	-	Start	37	19	86	1.159	1.162	1/4	212	0860.0	-
0830	4/2 /62	17	End	37	19		1.275	1.271	1/4	0	0884.9	24.9
1530	4/2 /62	-	Start	38	19	69	1.165	1.162	1/4	202	0884.9	-
0830	4/3 /62	17	End	38	19	85	1.274	1.277	1/4	0	0908.5	23.6
1530	4/3 /62	-	Start	39	19	74	1.178	1.177	1/4	184	0908.5	-
0830	4/4 /62	17	End	39	19		1.268	1.267	1/4	0	0930.0	21.5
1530	4/5 /62	-	Start	40	19	74	1.169	1.168	1/4	182	0930.0	-
0830	4/6 /62	17	End	40	19	81	1.269	1.271	1/4	0	0951.7	21.7
1530	4/9 /62	-	Start	41	19	69	1.160	1.157	1/4	210	0951.7	-
0830	4/10/62	17	End	41	19	77	1.270	1.270	1/4	0	0975.2	23.5
1530	4/11/62	-	Start	42	19	72	1.165	1.163	1/4	192	0975.2	-
0830	4/12/62	17	End	42	19	77	1.267	1.267	1/4	0	0997.9	22.7
Averages	-	-	-	-	-	-	-	1.164 1.271	-	197	-	23.2

		Meter reading dc kwhr	dc kwhr used	Charging amp	Charging volts	Open circuit volts	Specific gravity point change	Charger taps
1530	3/29/62	0373.7	-	30	L 36.4, R 36.4	L 35.0, R 35.0	-	2-3
0830	3/30/62	0392.3	18.6	2-8	L 40.3, R 40.3	L 39.4, R 39.4	115	2-3
1530	3/30/62	0392.3	-	30	L 36.3, R 36.3	L 34.9, R 34.9	-	2-3
0830	4/2 /62	0411.8	19.5	2-8	L 40.6, R 40.8	L 39.2, R 39.2	109	2-3
1530	4/2 /62	0411.8	-	28	L 36.7, R 36.7	L 34.9, R 34.9	-	2-3
0830	4/3 /62	0430.1	18.3	2-8	L 40.6, R 40.3	L 39.9, R 39.8	115	2-3
1530	4/3 /62	0430.1	-	29	L 36.8, R 36.8	L 35.0, R 35.0	-	2-3
0830	4/4 /62	0446.9	16.8	2-8	L 40.2, R 40.0	L 39.8, R 39.6	90	2-3
1530	4/5 /62	0446.9	-	27	L 36.9, R 36.9	L 35.5, R 35.5	-	2-3
0830	4/6 /62	0463.5	16.6	2-8	L 40.5, R 40.2	L 39.8, R 39.3	103	2-3
1530	4/9 /62	0463.5	-	28	L 36.4, R 36.4	L 34.8, R 35.8	-	2-3
0830	4/10/62	0482.2	18.7	2	L 40.0, R 39.9	L 39.8, R 39.6	113	2-3
1530	4/11/62	0482.2	-	28	L 37.0, R 37.0	L 35.0, R 35.0	-	2-3
0830	4/12/62	0499.9	17.7	2	L 40.2, R 40.0	L 39.5, R 39.3	104	2-3
Averages	-	-	18.0	-	L 36.6, R 36.6 L 40.3, R 40.2	L 35.0, R 35.0 L 39.6, R 39.5	107	-

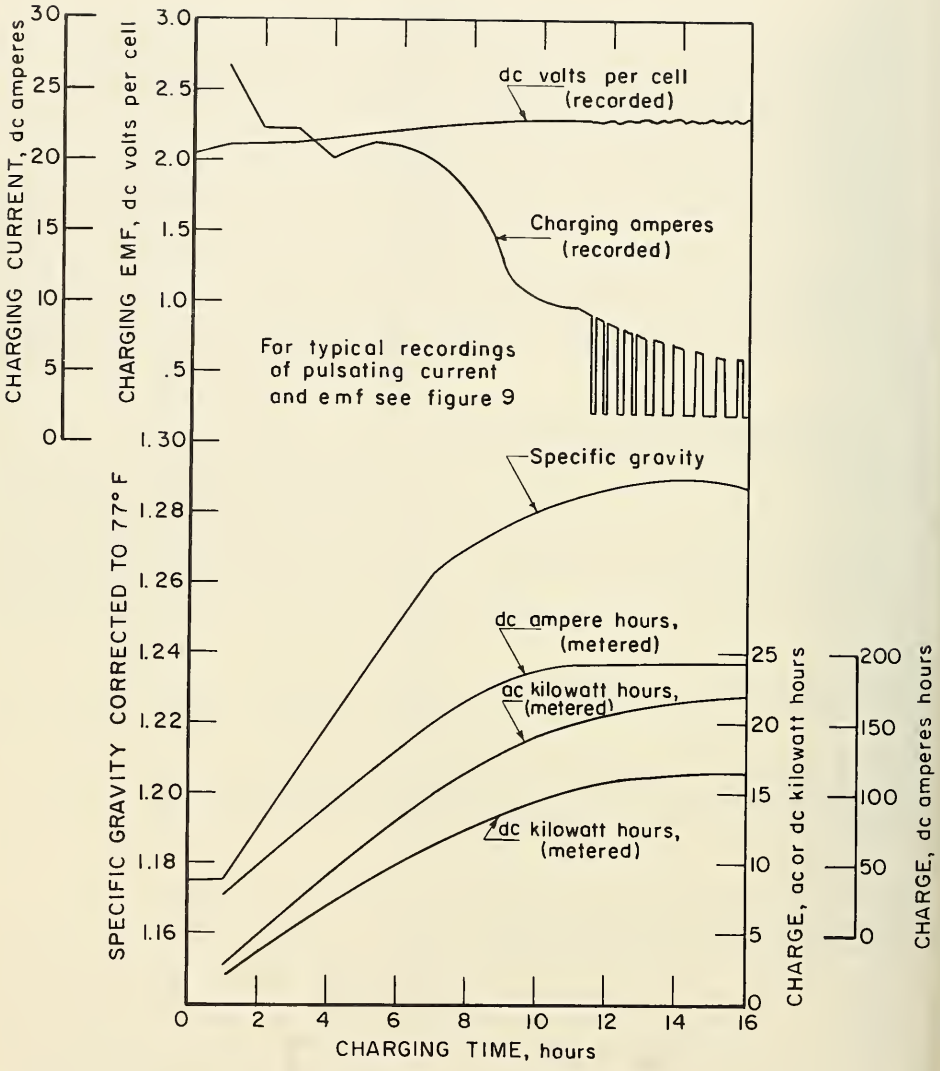
CHARGING CURRENT, dc amperes
CHARGING EMF, dc volts per cell
SPECIFIC GRAVITY CORRECTED TO 77° F
CHARGE, ac or dc kilowatt hours
CHARGE, dc amperes hours
CHARGING TIME, hours
dc volts per cell (recorded)
Charging amperes (recorded)
For typical recordings of pulsating current and emf see figure 9
Specific gravity
dc ampere hours, (metered)
ac kilowatt hours, (metered)
dc kilowatt hours, (metered)

FIGURE 8. - Motive Battery Charging Curves (Charge No. 121).

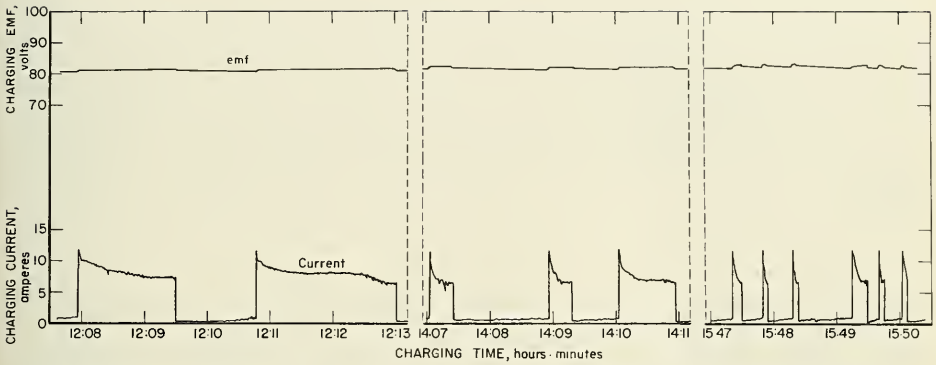

FIGURE 9. - Typical Recordings of emf and Current During Pulsating Charging Period.

At the start of charge 121, the charging voltage was 2.04 volts per cell, which was 0.15 volt per cell higher than the corresponding open circuit voltage at the start of charging. At the end of charge 121, the charging voltage was 2.32 volts per cell, which was only 0.05 volt per cell higher than the open-circuit voltage at full charge.

Activation of Motive Battery

Batteries that are new and batteries that have been idle for several days are below normal in available ampere-hour capacity, and require activation to obtain full capacity. A battery becomes fully activated by being subjected to several cycles of full discharges and charges. During initial operations, the new motive battery appeared to have gained full capacity and efficiency after the first 50 charges. The distance traveled per charge was initially about 20 miles, and the energy-mileage was about 1.1 miles per ac kilowatt-hour input; after 50 trips, the distance traveled per trip had increased to about 50 miles, and the energy-mileage had increased to 1.8 miles per ac kilowatt-hour input. Controlled variable studies were conducted only after the motive battery was fully activated.

Driving Characteristics

General

Handling characteristics of the electric truck were generally satisfactory. In ease of steering and braking, performance compared favorably to that of a conventional panel truck.

Traction was poor on snow-covered roads, in spite of the great weight of the truck and the use of a limited slip axle. The truck was unable to climb uphill on snow-covered roads that presented no difficulty to conventional trucks and passenger cars. The poor traction of the electric truck was attributed mainly to the low-friction tires.

Overall speed and acceleration of the truck was rather low, but suitable for driving in city traffic. Approximate road speeds for the truck were: 8 to 10 mph uphill, 15 to 25 mph on the level, and 30 to 40 mph downhill. Also, the maximum rating of 2,450 rpm for the motor imposed limits on the allowable truck speed; for example, at 1:1 gear ratio, maximum safe truck velocity was 36.3 mph. The low speed of the truck presented no difficulty in normal city traffic; however, on high-speed throughways and highways where traffic averages 40 to 60 mph, the low speed of the truck presents a potential traffic hazard.

Chart Recordings

To obtain graphic pictures of some of the main operating variables of the truck under various driving conditions, simultaneous recordings were made--speed, distance, motor field current, and motor emf. Figure 10 presents recordings of these variables for general driving and for stop-and-go driving. When the motor fields are in parallel, the motor current is two times the field current. The recordings are read from right to left.

The distance traveled by the truck was recorded in increments representing 100-foot lengths. The increments were marked by vertical marks superimposed on the velocity curve. Slightly longer marks are printed for 1,000-foot intervals. Shown in figure 10 are several distinct patterns which are typical of certain operations. Sections containing these patterns and the operations associated with the patterns are described as follows:

o-a: Current and voltage were off while the truck slowed down to cross some railroad tracks. The jagged parts of the velocity curve reflect jolting of the truck as it crossed the tracks.

a-b: Half voltage (about 36 volts) was applied at point "a," and the truck was accelerated along a fairly level stretch of road. The surge of field current resulting from the applied voltage was relatively low (45-50 amp) because the truck and its motor were already near normal speeds, with the motor generating a back emf.

b-c: Voltage was cut off, and brakes were applied. The truck then decelerated to a stop at a road intersection.

c-d: Half voltage was applied for about 4.2 seconds. The surge of field current exceeded the current scale of 250 amperes by an estimated 80 amperes. The truck accelerated from 0 to 5-1/2 miles per hour along level grade.

d-e: Voltage was cut off at "d" and the truck was brought to a stop at "e."

f: Charts were marked simultaneously to provide a point of chart alinement.

g1-g6: This section (0.7 to 1.9 minutes) represents acceleration of the truck under manual control where the accelerator pedal (a 5-position,

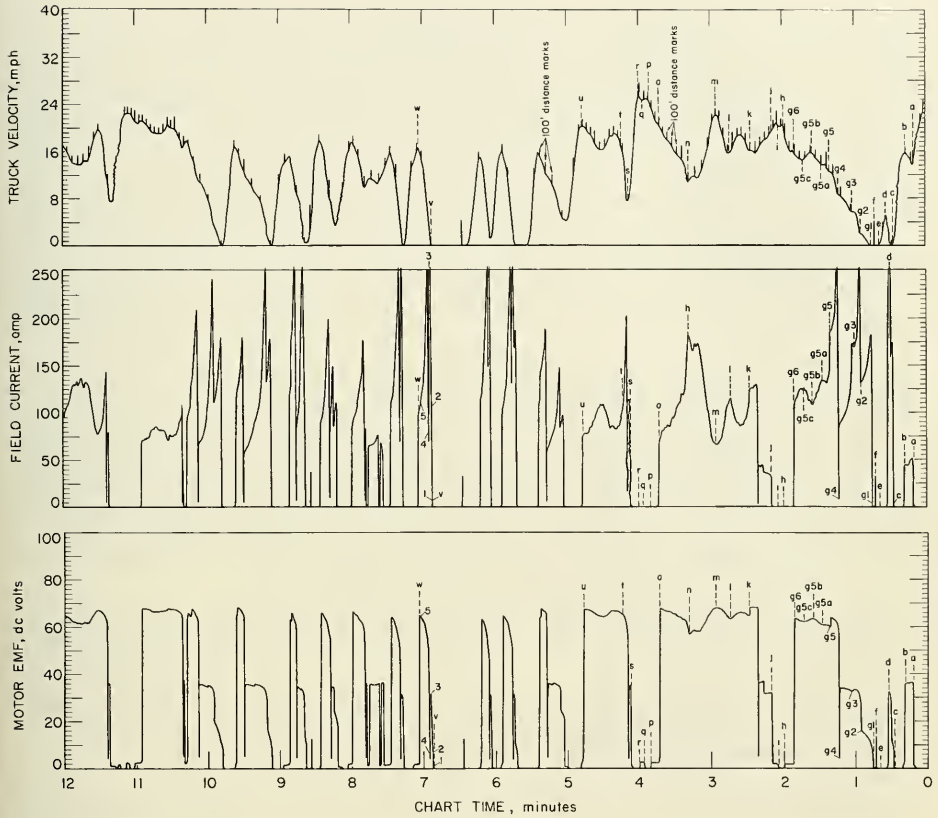

FIGURE 10. - Typical Recordings of Truck Velocity, Distance Traveled, Field Current, and Motor emf for Normal Driving and Stop-and-Go Driving (trip 133).

foot-operated switch) was arbitrarily held in successive switch positions for various periods of time. The points at which switch positions 1 through 5 were engaged are indicated, respectively, by points g1 through g5, inclusive. Battery, field, and resistor connections for the five switch positions are as follows:

Switch position	Battery	Field	Resistor
(1)	Parallel	Series	Series with fields
(2)	Parallel	Series	Shunted
(3)	Parallel	Parallel	Parallel to fields
(4)	Series	Series	Shunted
(5)	Series	Parallel	Parallel to fields

Switch position 5 is held from g5 to g6. The decline in current that follows each current surge is the result of the back emf increasing with increasing truck speed. A decline in road grade is indicated along sections g5a-g5b and g5c-g6 where the speed and applied emf increased and the current decreased. Uphill climbing is represented by section g5b-g5c where an increase in current attended a decrease in speed and emf.

g6-h: The truck coasted downhill without the application of brakes. A back emf of about 2 volts was registered.

h-i: Upon application of the footbrake, the back emf no longer registered, and the truck decreased in speed.

i-j: The footbrake was released at "i." The truck reached the bottom of a dip, then began coasting uphill.

j-k: Emf was applied at "j" under manual control. Switch position 5 was closed at "k." The truck lost speed as it ascended a hill.

s-t: The truck was accelerated under automatic control. Automatic control is obtained by completely and quickly depressing the accelerator pedal. This activates timing devices which automatically control the switching and the time of contact for each switch position. The time of switching for automatic control (compare s-t against g1-g5). Point "t" represents contact of switch position number 5. The surge of field current was relatively low for this start-up because the truck was already in motion.

t-u: The truck was running at a normal pace in switch position 5. Changes in road grade were reflected in changes in truck speed, field current, and to a much lesser extent, motor emf.

v-w: Under automatic control the truck was started from rest. Starting from rest produced a large surge of field current that exceeded 250 amperes. Points 1 through 5 designate where the respective switch positions were engaged.

The operating patterns described above are tabulated in table 4 for quick reference.

TABLE 4. - Regions in figure 10 reflecting various truck operations

Acceleration (manually controlled)		Acceleration (automatically controlled)		Normal cruising (switch positions)		Coasting		Braking
Truck initially at rest	Truck initially moving	Truck initially at rest	Truck initially moving	Downhill	Uphill	Downhill	Uphill	
c-d	a-b	v-w	s-t	g5a-g5b	g5b-g5c	g6-h	i-j	o-a
g1-g6	j-k[1]	-	-	g5c-g6	m-n	o-p	-	b-c
-	-	-	-	l-m	-	q-r	-	d-e
-	-	-	-	n-o	-	-	-	h-i
-	-	-	-	-	-	-	-	p-q
-	-	-	-	-	-	-	-	r-s

[1]Starting uphill.

Range Tests

Range

After the initial series of trips was concluded and the battery appeared to be fully activated, extensive trips of approximately 50 miles were made over a moderately hilly course to bring the motive battery reasonably close to exhaustion. Thus, the general performance of the vehicle was determined during the early stages (trip Nos. 62, 64, and 65) of the overall program. These trips were made under standard conditions: over dry macadam or concrete roads, on moderate temperature days (between 40° and 80° F), with the tire pressure at 60 psig, and carrying a standard payload of 868 pounds. Batteries were fully charged before each trip. Hereafter, only deviations from such standard conditions will be noted.

Similarly, a second series of general performance tests (trips 228, 229, and 230) was conducted near the end of the overall test program to redetermine the performance of the truck. The course for the second series of trips contained more hills than the original course. Odometer readings at the start of the first and second series of tests were 2,290 and 7,274 miles, respectively. Summary data with estimates of the standard deviations of the tests are presented in table 5.

TABLE 5. - Summary of general performance during range tests
(Dry roads, moderate temperatures, tire pressure 60 psig, standard payload of 868 lb)

Trip numbers	62, 64, 65		228-230	
Test series numbers	1		2	
Dates of tests	July 1962		June 1963	
	Average	Estimated standard deviation	Average	Estimated standard deviation
Trip data:				
Total running time....hr	2.71	-	2.56	-
Total time stopped....hr	0	-	1.0	-
Trip distance....miles	50.9	-	50.3	-
Average running speed....mph	18.8	0.39	19.7	0.09
Gross haulage....ton-miles	140.9	-	139.3	-
Ampere-hours used	230	1.0	249	2.0
Charging data:				
Charging time....hr	17	-	17	-
Input, ac kwhr	26.9	.2	30.8	.5
Input, dc kwhr	21.8	.4	24.7	.8
Specific gravity point increase[1] corrected to 77° F	142	7.5	135	12.2
Performance:				
Ton-miles per ac kwhr	5.24	.22	4.53	.5
Miles per ac kwhr	1.89	.05	1.64	.5
Miles per ampere hour	.222	.001	.202	.001
Miles per specific gravity point change	.360	.019	.382	.022

[1]A specific gravity change of 1,000 equals a change of 1,000 points.

Since it was impractical to operate the vehicle until its battery was completely exhausted, operation was halted before signs of complete battery exhaustion occurred. The practical range of the truck, therefore, was arbitrarily defined as the distance traveled after using 85 percent of the amp-hour (6-hour rate) capacity of the battery. The ultimate range was then assumed to be $\frac{100}{85}$ x the practical range.

For test series 1 and 2, the average practical ranges were, respectively, 51.8 and 47.3 miles; also the corresponding ultimate ranges were 60.9 and 55.6 miles. The lower range attained in test 2 was attributed largely to the fact that more hills were encountered during the second test series than in the first series. Another contributing factor to the reduction in range was that the additional hills traveled in the second series of tests were near the end of the trip; that is, at the time when the battery was at its lowest efficiency.

Energy Used

As shown in table 5, for test series 1, the average ac power input to the rectifier for the motive battery was 26.9 kwhr per trip, while the average dc power input to the motive battery was 21.8 kwhr per trip. Under these conditions, the average efficiency of the motive battery rectifier was 81.2 percent. In test series 2, the average rectifier efficiency was 80.2 percent.

The average amp hr consumed per trip during the range tests was 230 amp hr for test series 1 and 249 amp hr for test series 2. Thus the trend in amp hr agrees with the observation that more hills were encountered in test series 2 than in test series 1. Energy consumption as indicated by the changes in specific gravity of battery acid, however, was not consistent with this observation. The average change in specific gravity of 142 points per charge for test series 1 was greater than the average specific gravity change of 135 points per charge for test series 2. Although estimated standard deviation of the change in specific gravity is rather high, 5 and 9 percent, no explanation has been found for the apparent inconsistency of the trend in specific gravity change.

Overall Performance

The overall performance of the truck during the range tests is expressed in several ways in table 5. Three mileages were expressed as miles traveled per unit ac kwhr input, miles traveled per unit amp hr used, and miles traveled per unit change in specific gravity points. Another overall performance factor was the specific haulage, which was defined as the gross haulage per unit ac kwhr energy input, where the gross haulage was the gross weight of the truck, in tons, times the miles traveled.

As shown in table 5, and with the exception of the mileage based on the unit change in specific gravity, all specific performance factors of the truck were greater for test series 1 than for test series 2. For example, the miles traveled per ac kwhr input was 1.89 in test series 1, and 1.64 in test series

2, and similarly the specific haulage in ton-miles per ac kwhr input was 5.24 for test 1 and 4.53 for test 2. The variation in the value of each performance factor shows that variations in terrain produce significant effects.

CONTROLLED EXPERIMENTS

Standard Operating Conditions

To study the effect of certain operating variables and road conditions upon the specific performance of the truck, numerous trips were made over two calibrated courses (standard courses 1 and 2) and at controlled conditions. Although the average grade of any round-trip course is zero, a measure of the hilliness of a course is provided by the average positive grade over the entire course. The average positive grade of a course is defined as: (the sum of the products of all positive grades encountered × their respective increments of distance) ÷ (total distance of the course). Average positive grade for courses 1 and 2, respectively, were 1.11 and 1.85 percent. The other reference conditions were the same as those described for the series of range tests. Each experiment was generally repeated five times. The data reported in these experiments are the averages of at least 3 to 5 experiments.

Effect of Payload

The truck was operated over standard courses 1 and 2 at reference conditions and also at payloads of 1,068, 1,268, and 1,468 pounds. The results are summarized in tables 6 and 7. The gross haulage in ton-miles per ac kwhr and mileage in miles traveled per ac kwhr input are plotted as functions of payload in figure 11. The specific gravity of the battery acid and the miles traveled per amp hr dc (metered) are also plotted as functions of payload in figure 12.

As indicated in tables 6 and 7 and figures 11 and 12, the performance of the truck in specific mileage declined with increase in payload. As the payload was increased from 868 to 1,468 pounds (a 10.8 percent increase in gross weight), specific mileage of the truck on course 1 declined 5.0, 12.0, and 71.1 percent in miles per kwhr ac input, miles per amp hr used, and miles per point change in specific gravity, respectively. Conversely, the performance increased 5.6 percent when it was expressed as specific haulage in ton-miles per kwhr ac input. One possible explanation of this relationship is that the truck motor probably operates more efficiently at the higher payloads; and because ton-miles is a unit of energy, the increase in energy efficiency was more accurately expressed in specific haulage than in specific mileage.

The 12-percent decline in miles per amp hr for course 1 is significantly greater than the corresponding percentage change in miles per kwhr ac and in miles per point change in specific gravity. Since the distance traveled was constant, this comparison shows that amp hr as an indicator of battery usage is more sensitive than either specific gravity of kwhr ac input. The same conclusion was reached for operation on course 2.

TABLE 6. - Effect of various payloads upon truck operation on course No. 1
(Dry road, generally moderate temperature,
60-psig tire pressure)

	Trip numbers							
	71, 75, 77, 78, 83		98-101, 105		107-108, 110-112		114-116, 118, 120	
	Average	Estimated standard deviation	Average	Estimated standard deviation	Average	Estimated standard deviation	Average	Estimated standard deviation
Trip data:								
Payload....lb....	868	-	1,068	-	1,268	-	1,468	-
Running time....hr....	1.86	-	1.88	-	1.88	-	1.90	-
Trip distance....miles....	34.3	-	34.3	-	34.3	-	34.3	-
Average running speed....mph....	18.4	0.4	18.2	0.3	18.3	0.3	18.1	0.2
Gross haulage....ton-miles....	94.82	-	98.41	-	101.84	-	105.27	-
Ampere-hours used....	165	-	172	-	177	-	188	-
Charging data:								
Time....hr....	17	-	17	-	17	-	16.8	-
Input, ac kwhr....	21.3	-	21.7	-	22.1	-	22.4	-
Input, dc kwhr....	16.3	-	16.6	-	17.0	-	17.1	-
Specific gravity at 77° F, points increase....	97.8	-	102.0	-	106.6	-	105.4	-
Performance:								
Ton-miles per ac kwhr....	4.45	.25	4.54	.10	4.61	.15	4.70	.10
Miles per ac kwhr....	1.61	.09	1.58	.03	1.55	.05	1.53	.03
Miles per ampere-hour....	.208	.004	.200	.002	.194	.003	.182	.004
Miles per points increase....	.351	.019	.337	.016	.322	.010	.326	.013

TABLE 7. - Effect of various payloads upon truck operation on course No. 2
(Dry road, generally moderate temperature,
60 psig tire pressure)

	Trip numbers							
	126, 127, 145-147		128-132		134, 136-138		139-141, 143,149	
	Average	Estimated standard deviation	Average	Estimated standard deviation	Average	Estimated standard deviation	Average	Estimated standard deviation
Trip data:								
Payload....lb....	868	-	1,068	-	1,268	-	1,468	-
Running time....hr....	1.79	-	1.82	-	1.85	-	1.86	-
Trip distance....miles....	27.4	-	27.4	-	27.4	-	27.4	-
Average tunning speed....mph....	15.3	0.4	15.1	0.3	14.8	0.3	14.8	0.4
Gross haulage....ton-miles....	75.87	-	78.61	-	81.35	-	82.39	-
Ampere-hour used....	169	-	168	-	184	-	192	-
Charge data:								
Time....hr....	17	-	17	-	17	-	17	-
Input, ac kwhr....	21.3	-	21.3	-	22.0	-	22.9	-
Input, dc kwhr....	16.8	-	16.3	-	17.1	-	19.2	-
Specific gravity at 77° F, points increase....	97.0	-	97.2	-	102.5	-	104.4	-
Performance:								
Ton-miles per ac kwhr....	3.57	.12	3.70	.08	3.70	.11	3.68	.15
Miles per ac kwhr....	1.29	.04	1.29	.03	1.25	.04	1.20	.05
Miles per ampere-hour....	.162	.012	.163	.004	.149	.002	.143	.003
Miles per points increase....	.285	.009	.282	.009	.267	.010	.263	.014

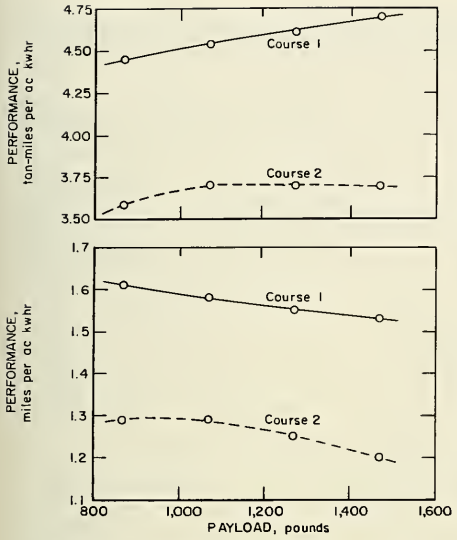

FIGURE 11. - Effect of Payload Upon Ton-Miles per ac kwhr and Miles per ac kwhr (moderate temperature, dry road, tire pressure 60 psig).

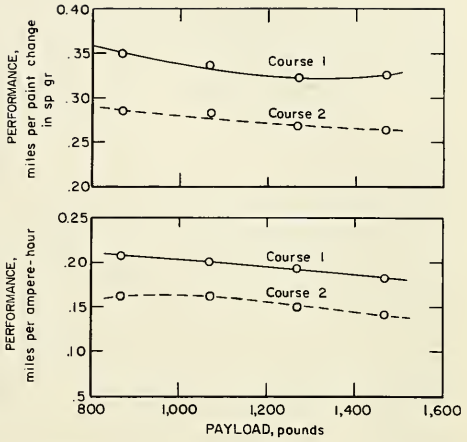

FIGURE 12. - Effect of Payload Upon Miles per Point Change in Specific Grovity and Miles per Ampere-Hour (moderate temperature, dry road, tire pressure 60 psig).

The estimated standard deviations presented in tables 6 and 7 indicate the spread of the values of the various performance factors. When expressed as percentages of their means, the estimated standard deviations range from about 1 to 6 percent. Such variations are of little significance to the trend of the data.

The truck's performance is considerably lower over course 2 than over course 1. This is attributed to course 2 being more hilly than course 1 and, to a small degree, to course 2 being shorter than course 1.

Effect of Wet Roads

To determine the effect of wet roads upon performance, trips 113, 117, 119, and 120 were conducted over standard course 1 in rainy weather carrying a payload of 1,468 pounds. The average operating data for these trips are presented in table 8, where they are compared with operation over the same course with the same payload in dry weather. The results indicate that the average truck speed decreased 0.5 mile per hour, and the specific haulage, in ton-miles per ac kwhr charged, decreased 5.5 percent because of wet road conditions.

TABLE 8. - Effect of road condition (wet vs dry) upon truck operation
(Course No. 1, moderate temperature, 60-psig tire pressure, 1,468 lb payload)

Trip numbers	114, 116, 118, 121		113, 117, 119, 120	
Weather[1]	Moderate		Moderate	
Road conditions	Dry		Wet	
	Average	Estimated standard deviation	Average	Estimated standard deviation
Trip data:				
Running time.....hr....	1.90	-	1.95	-
Trip distance.....miles....	34.3	-	34.3	-
Average running speed.....mph....	18.1	0.2	17.6	0.1
Gross haulage.....ton-miles....	105.27	-	105.27	-
Ampere-hours used.....	188	-	203	-
Charging data:				
Time.....hr....	16.8	-	17.0	-
Input, ac kwhr.....	22.4	-	23.7	-
Input, dc kwhr.....	17.1	-	18.3	-
Specific gravity at 77° F, points increase.....	105.4	-	112.8	-
Performance:				
Ton-miles per ac kwhr input.....	4.70	.1	4.44	.07
Miles per ac kwhr.....	1.53	.03	1.45	.02
Miles per ampere-hour.....	.183	.004	.169	.002
Miles per specific gravity point change.....	.326	.013	.305	.009

[1]Moderate temperatures are 40° to 80° F.

Effect of Road Grade and Gear Ratio

To determine the effect of road grade upon truck performance, a series of tests was conducted in which the truck was driven at essentially constant speed over six test sections. Test sections 1 through 6, respectively, have grades of 9.66, 8.09, 5.60, 3.40, 2.37, and 0.82 percent. Recordings were taken simultaneously of speed, distance, field current, and motor emf. Some of the recordings gathered over the 8.09-, 2.37-, and 0.82-percent grades are shown in figure 13, which is typical of the data collected in this series of tests.

To minimize deviations in velocity during these tests, the truck was brought to the highest speed that it could maintain on the test section before it entered the test section. The average deviation in velocity ranged between 2.5 and 4.3 percent.

Start and finish of each test were designated on the recordings by extra long marks simultaneously printed by all three chart pens. This reference marking of charts was achieved by the driver pressing a single control button. Marks tagged with odometer readings identify the start of a new test.

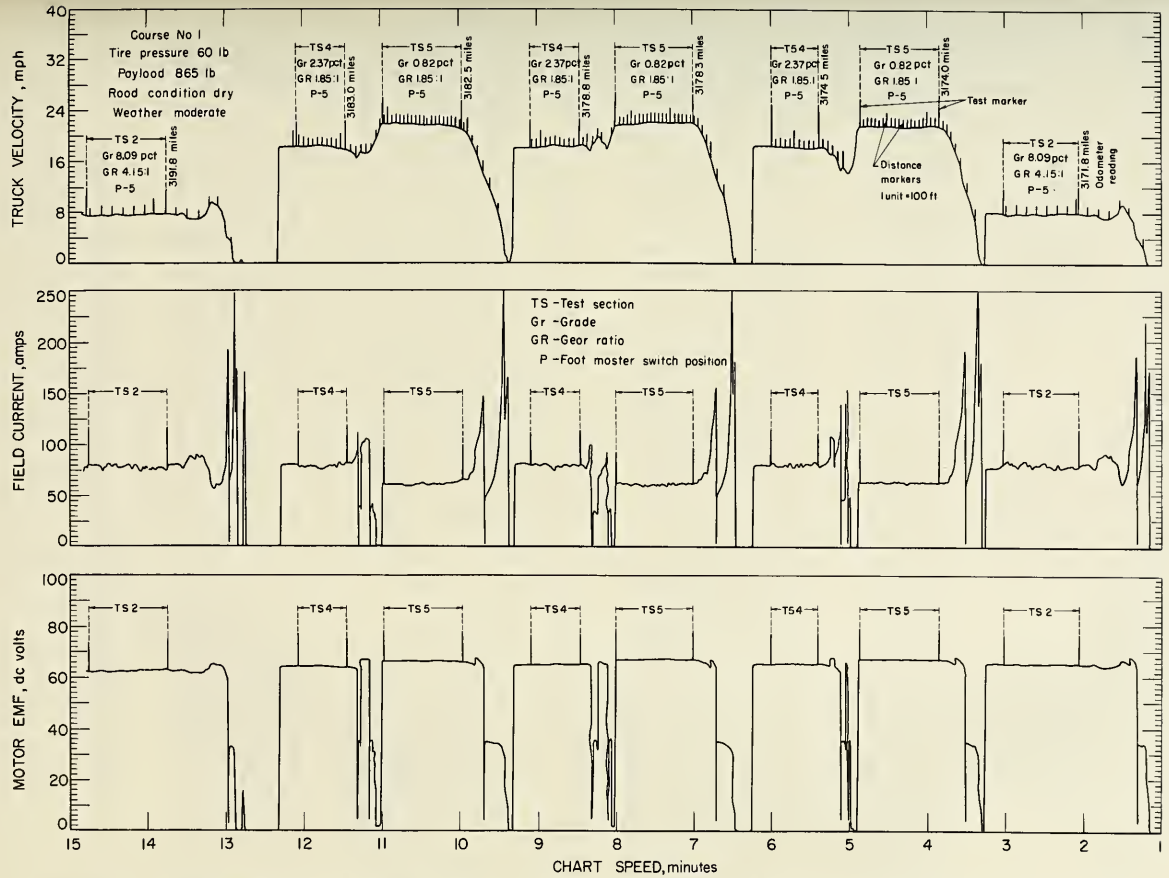

FIGURE 13. - Recordings of Truck Speed, Distance Traveled, Field Current, and Motor emf Over Test Sections 2, 4, and 5 (trip number 87).

It was necessary to use different gearshift ratios to maintain a constant speed on the different road grades. The nominal gearshift ratios and overall gear ratios used for the various grades were:

Shift ratio	Overall ratio	Grade, percent
1.85:1	9.95:1	0.82, 2.37, 3.40
3.15:1	17.0:1	3.40, 5.60
4.15:1	22.3:1	8.09, 9.66

The 1:1 gear resulted in an excessive draw of current even at the 0.82 grade; therefore, this gear could not be used. Other conditions maintained in this basic test series were standard. Additional tests were conducted on the 5.60- and 9.66-percent grades with the truck carrying payloads of 1,068, 1,268, and 1,468 pounds.

The miles traveled per dc kwhr input to the motor were determined for these tests from the recorded distance and from integration of the voltage and amperage charts. The estimated standard deviation from the mean for these mileage values ranged from 0.9 to 3.9 percent. In figure 14, average values of the mileage in miles traveled per dc kwhr input to the motor are plotted as a function of the road grade for a constant payload of 868 pounds. Other points are presented in figure 14 indicating the truck's performance at 1,068-, 1,268-, and 1,468-pound payloads.

Truck performance, expressed as specific haulage in ton-miles per dc motor input, is similarly plotted against road grade in figure 15.

Reference to figures 14 and 15 indicates that an increase in road grade produces a nonlinear decrease in both the mileage and specific haulage. At standard payload, both of these performance factors decreased about 74 percent as the road grade increased from 0.82 to 9.66 percent. As the payload was increased from 868 to 1,468 pounds, the mileage decreased, respectively, 24.8 and 19.3 percent on the 5.6- and 9.66-percent grades. The specific haulage, on the other hand, remained virtually unaffected by increases in payload.

When the truck was operated at gearbox ratios of 1.85:1 and 3.15:1 on 3.4 percent grade (figs. 14 and 15), it was found that the mileage and specific haulage were slightly increased by the increase in gear ratio. A 6.5-percent increase in mileage and a 5.7-percent increase in specific haulage were obtained when the gearbox ratio was increased from 1.85:1 to 3.15:1 during operation on the 3.4-percent grade. When the specific haulage values on the smoothed curve in figure 15 are inverted, the following linear relation results:

$$\left(\frac{\text{motor input, dc kwhr}}{\text{ton-mile}}\right) = 0.0425 \text{ (percent grade)} + 0.101.$$

It was observed that the gear ratio appreciably affected other important operating variables such as the truck velocity, dc power drawn by the motor, motor current (which is two times field current for foot switch position 5), and the motor emf. These operating variables are plotted against road grade

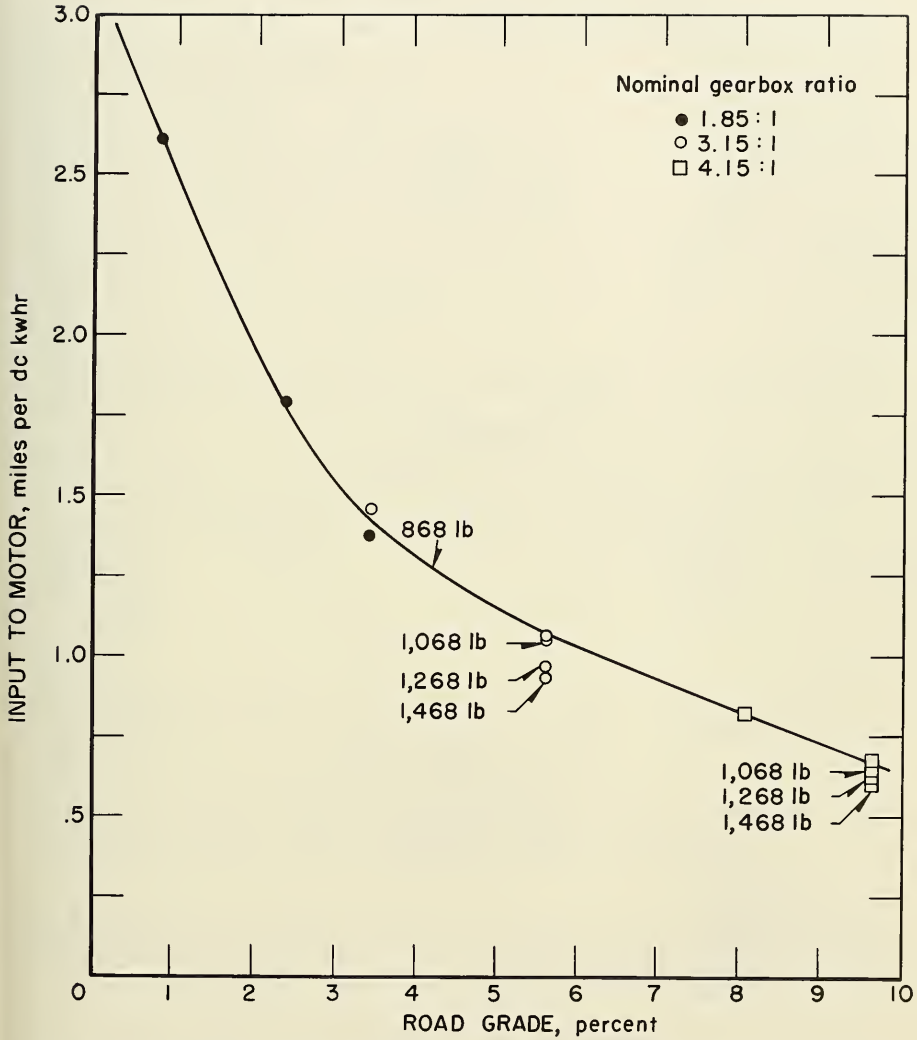

FIGURE 14. - Effect of Road Grade and Gearbox Ratio Upon Miles Traveled per dc kwhr Input to Motor (payload at indicated lbs, moderate temperature, 60 psig tire pressure, dry road).

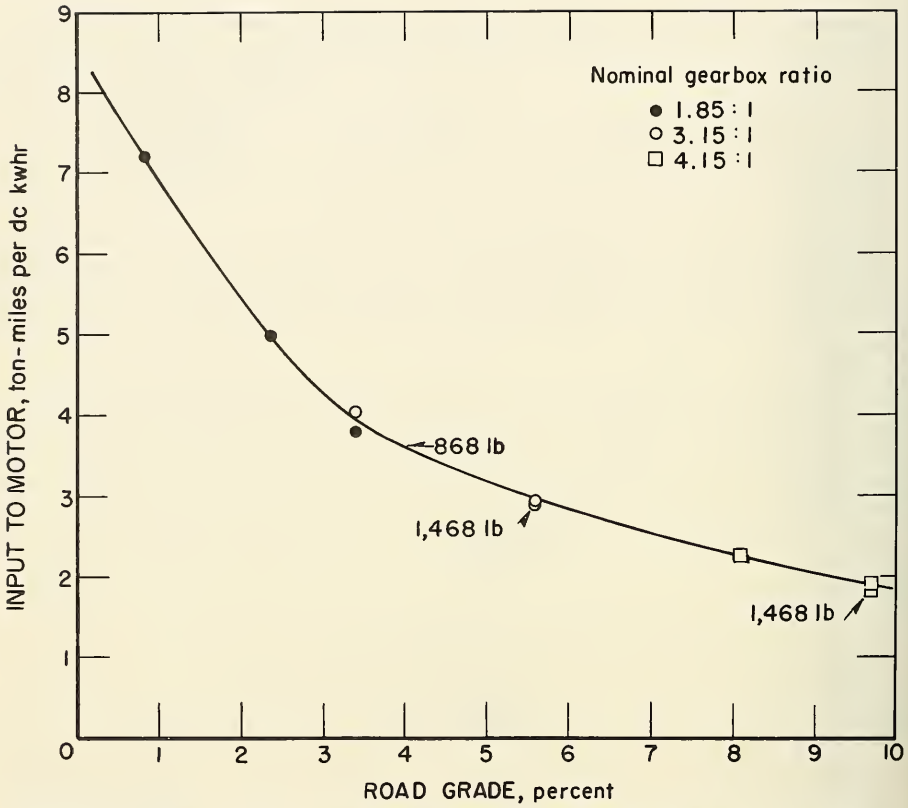

FIGURE 15. - Effect of Road Grade and Gearbox Ratio Upon Ton-Miles per dc kwhr Input to Motor (payload at indicated lbs, moderate temperature, 60 psig tire pressure, dry road).

at constant gear ratios and payloads in figures 16 and 17. Values of motor and gear efficiency corresponding to the test conditions were estimated from the traction equation and assumptions are given in the appendix. These values are also presented in figure 17.

The curves in figures 16 and 17 for operation at constant gearbox ratios of 1.85:1, 3.15:1, and 4.15:1 and at a constant payload of 863 pounds, show that the power and current drawn by the motor increased greatly with increase in road grade. The truck velocity, on the other hand, decreased sharply, while the motor emf dropped only slightly. Increases in payload significantly increased the power and current drawn by the motor, and lowered the truck velocity, as well as the efficiency of motor and gear. Decreases that resulted in motor emf were small.

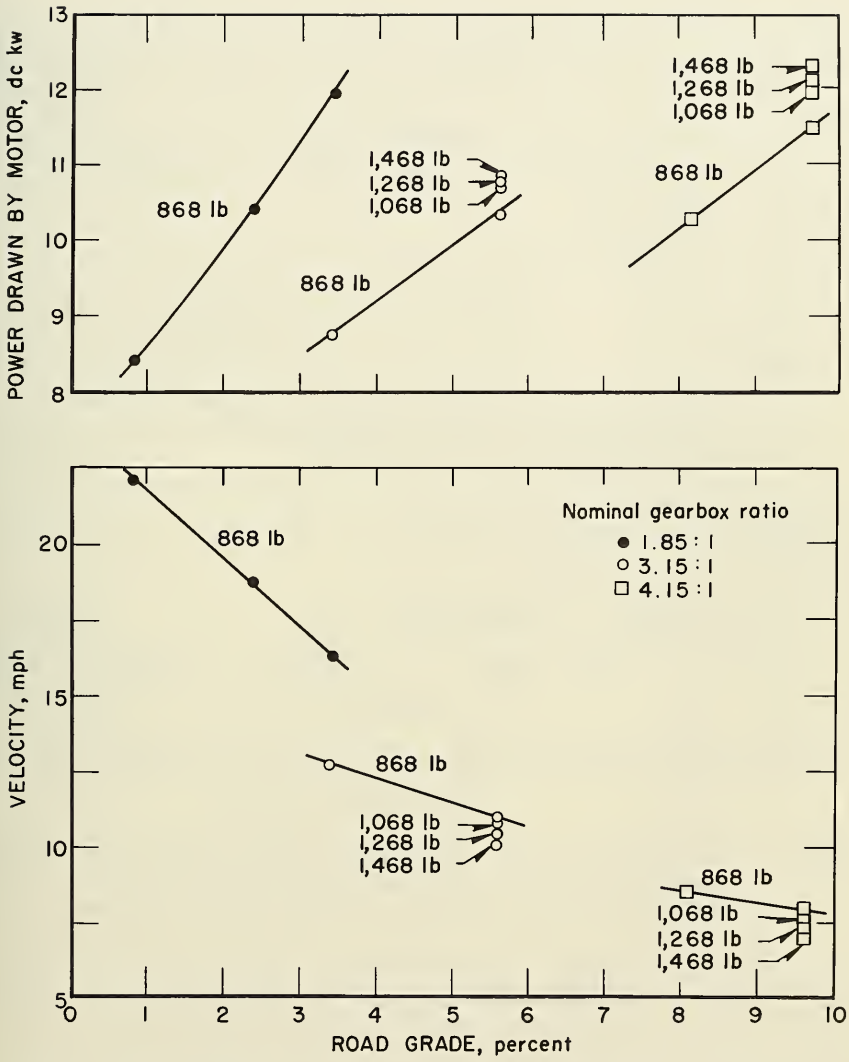

FIGURE 16. - Effect of Road Grade and Gearbox Ratio Upon Power Drawn by Motor and Truck Velocity (payload at indicated lbs, moderate temperature, 60 psig tire pressure, dry road).

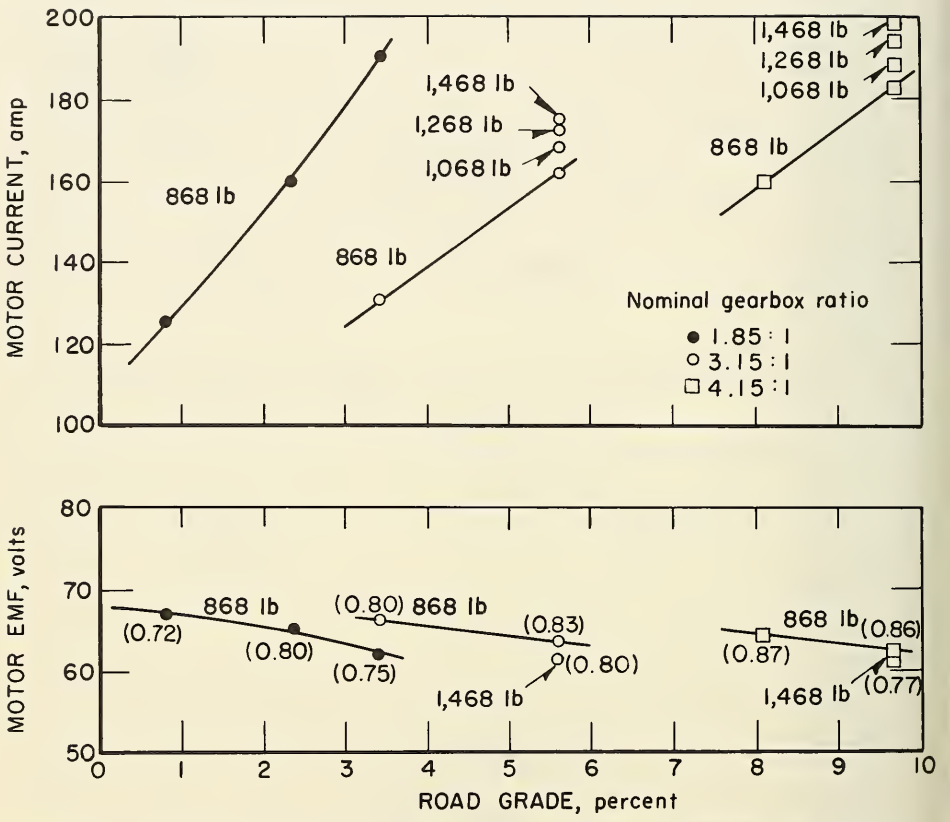

FIGURE 17. - Effect of Road Grade and Gearbox Ratio Upon Motor Current and emf (payload at indicated lbs, moderate temperature, 60 psig tire pressure, dry road). Value of product of motor and gear efficiencies ($e_m \cdot e_{ge}$) given in parentheses.

Increases in gear ratios were necessary in order to climb the higher percent grade roads. As shown in figures 16 and 17 for truck operation on the 3.40-percent grade, an increase in gear ratio from 1.85:1 to 3.15:1 reduced the draw of power by 36 percent, the motor current by 45 percent, and the velocity of the truck by 27 percent. On the other hand, both the motor emf and the efficiency of motor and gear increased by approximately 6 percent.

Effect of Tire Pressure

Tire pressures were recorded before each trip, and were normally maintained at the recommended pressure of 60 psig. To determine the effect of a

lower tire pressure, trips 217 through 219 were made over course No. 1 with tire pressures maintained at 50 psig. Trips 213, 214, and 216 were similar except that tire pressures were at the standard 60 psig. Summaries of the average test results are presented in table 9.

The performance data in table 9 show that the lower tire pressure resulted in lower truck performance. Percent losses in some performance factors were as follows:

Factor:	Percent loss
Ton mile per ac kwhr	3.7
Miles per ac kwhr	3.7
Miles per amp hr	5.5
Average velocity	2.2

TABLE 9. - Effect of tire pressure upon truck operation
(Course No. 1, dry roads, moderate temperatures, payload 868 lb)

	Trip numbers			
	213, 214, 216		217-219	
	Average	Estimated standard deviation	Average	Estimated standard deviation
Trip data:				
Tire pressure....psig...	60	-	50	-
Total running time....hr...	1.77	-	1.81	-
Total time stopped....hr...	0	-	0	-
Trip distance....mile...	34.3	-	34.3	-
Running speed....mph...	19.42	0.180	18.99	0.121
Gross haulage....ton-miles...	94.98	-	94.98	-
Ampere-hours used....	171.3	-	181.0	-
Charging data:				
Time....hr...	17	-	17	-
Input, ac kwhr....	22.5	-	23.4	-
Input, dc kwhr....	18.0	-	18.9	-
Average specific gravity at 77° F, points increase....	90.3	-	101.3	-
Performance:				
Ton-miles per ac kwhr input....	4.215	.076	4.060	.076
Miles per ac kwhr....	1.523	.027	1.466	.028
Miles per ampere-hour....	.200	.002	.189	.004
Miles per specific gravity points increase....	.381	.024	.339	.013

Effect of Battery Condition

Time of Charging of Battery

To determine the effect upon overall truck performance of reducing the length of time of charging the battery, three series of tests were conducted in which only the length of time of charge was varied. The charging times were 17, 13, and 9 hours. The average data showing the overall truck performance and battery voltages for these test series are presented in table 10.

TABLE 10. - Effect of time of charging of battery upon overall truck performance (Course No. 1, moderate temperature, dry road, 868-lb payload, 60-psig tire pressure)

Performance determination	Average for trips 213-215	Estimated standard deviation	Average for trips 220-224	Estimated standard deviation	Average for trips 239-241	Estimated standard deviation
Trip Data						
Charging time.....hr...	17	-	13	-	9	-
Total running time.....hr...	1.77	-	1.76	-	1.76	-
Trip distance.....miles...	34.3	-	34.3	-	34.3	-
Average speed.....mph...	19.42	0.18	19.53	0.19	19.45	0.13
Gross haulage....ton-miles...	94.42	-	94.98	-	94.98	-
Ampere-hour used.....	171.3	1.5	172.6	5.6	177.3	6.0
Charging Data						
Left half, open circuit voltage:						
Before charge (18 cells)...	35.7	0.3	35.8	0.4	35.3	0.10
After charge (18 cells)....	40.0	.4	38.0	.05	37.9	.20
ac kwhr.....	22.5	.4	21.2	2.4	17.1	2.1
dc kwhr.....	18.0	.2	17.1	2.1	13.9	1.6
Specific gravity at 77° F, point increase.....	90.3	.6	90.4	7.4	87.7	6.7
Performance						
Ton-miles per ac kwhr.....	4.22	0.08	4.53	0.560	5.61	0.64
Miles per ac kwhr.....	1.52	.03	1.63	.20	2.03	.23
Miles per ampere-hour.....	.200	.002	.199	.006	.194	.007
Miles per specific gravity point change.....	.381	.024	.381	.031	.393	.031

The data in table 10 show that reductions in charging time from 17 to 13 hours, and from 17 to 9 hours brought 7.4 and 32.9-percent increases, respectively, in the ton miles traveled per ac kwhr charged, and 7.2 and 33.6-percent increases in the miles traveled per ac kwhr charged. These increases in average overall performances were largely the direct result of less ac kwhr being charged to the system. On the other hand, when the truck performance was expressed in miles traveled per amp hr used, it decreased slightly with the reduction in charging time. The reduction in this performance factor resulted from increased amp hr which resulted from operating at slightly lower discharge voltages. Lowering of the discharge voltage is indicated by the open circuit voltage of the battery being lower with shorter charging periods. Other consequences of decreased operating voltage were lower truck velocities and larger current flows, all of which resulted in increased amp hr. These trends in motor voltages, current, and truck velocity are also evident in table 11,

which presents instantaneous truck performance data for operation on the 8.09-percent grade test strip during this same series of tests.

TABLE 11. - Effect of time of charging of battery upon instantaneous truck performance on 8.09-percent grade
(Course No. 1, moderate temperature, dry road, 868-lb payload; 60-psig tire pressure.)

	Number of hours charge					
	17		13		9	
	Average	Estimated standard deviation	Average	Estimated standard deviation	Average	Estimated standard deviation
Grade, percent.....	8.09	-	8.09	-	8.09	-
Number points.....	6	-	6	-	6	-
Motor voltage, volts:						
Average.....	65.1	1.7	64.9	1.5	63.6	2.1
Motor current, amp:						
Average.....	159.0	1.8	158.2	2.2	160.6	1.2
Battery power output, kw:						
Average.....	10.36	.38	10.28	.38	10.22	.42
Velocity, mph:						
Average.....	8.76	.03	8.71	.23	8.68	.27
Miles traveled per dc kwhr:						
Average.....	.83	.02	.85	.02	.85	.02
Ton-miles per dc kwhr:						
Average.....	2.35	.06	2.35	.06	2.36	.04

Concerning the effect of time of charging, it can be concluded, generally, that prolonged charging of the battery (17 hours) can result in a sizeable waste of electric energy. A compensating advantage of the prolonged 17-hour charge, however, is that the battery does become completely charged, and the need of performing a weekly equilizing charge on the battery is eliminated. Shorter charging periods provide more overall efficiency, but the shorter the daily charging period, the greater becomes the need of using equalizing charges. Finally, as the period of charging is shortened, the inherent danger of completely exhausting the battery while the truck is in road service is increased.

Capacity Discharged

The properties of lead-acid batteries vary with the capacity discharged or with the number of amp hr used. Characteristically, the discharge voltage, current, and power output decrease as the amp hr capacity of a battery is expended against a constant load. To determine the effect of the state of charge of the motive battery upon the instantaneous performance of the truck, a series of tests was conducted on the 8.09-percent grade and 0.82-percent grade test sections at different levels of capacity discharged of the battery (amp hr used). While the truck was held at constant speed over the test

strips, recordings were taken of motor voltage, field current or one-half motor current truck velocity, and distance traveled. The results of the tests are shown in table 12.

TABLE 12. - Effect of discharged capacity of battery upon instantaneous truck performance on 8.09- and 0.82-percent grades
(Course 1, moderate temperature, dry road, 828-lb payload, 60-psig tire pressure)

	Capacity discharged, amp hr used			
	5	160	9	173
Grade, percent	8.09	8.09	0.82	0.82
Number points	3	3	4	3
Motor voltage, volts:				
Average	66.2	61.1	67.7	62.6
Estimated standard deviation	.5	.7	.3	.3
Motor current, amp:				
Average	162.6	160.6	128.8	122.8
Estimated standard deviation	.4	.8	2.8	.6
Battery power output, kw:				
Average	10.76	9.80	8.72	7.68
Estimated standard deviation	.08	.12	.20	.06
Velocity, mph:				
Average	9.03	8.36	23.2	22.1
Estimated standard deviation	.10	.08	.2	.3
Miles traveled per dc kwhr:				
Average	.83	.85	2.67	2.88
Estimated standard deviation	.06	.04	.30	.26
Ton-miles per dc kwhr:				
Average	2.33	2.35	7.38	7.96
Estimated standard deviation	.03	.03	.21	.21

The results given in table 12 show that as the capacity of the battery was discharged, the battery voltage, current, and truck velocity decreased and instantaneous performance, as represented by the miles traveled per dc kwhr and ton-miles per dc kwhr, increased. These trends are similar to those obtained when the charging time is shortened.

Effect of Stop-and-Go Driving

To reproduce the stop-and-go driving conditions typical of those on home delivery routes, a series of stop-and-go driving tests was conducted. A 20-mile portion of course 1 was established as the course for the tests. Driving conditions with regard to temperature, weather, tire pressure, battery charge, and payload were standard. To allow for traffic control and the need to change gears, the minimum number of stops was set at an average of one stop per 1-1/3 miles or three-quarter stop per mile. Tests were also conducted at 5, 7-1/2, and 10 stops per mile. The length of time spent at each stop throughout a test was arbitrarily set at either 1/2 or 1-1/2 minutes.

A summary of the test data is presented in table 13. The total time on any test trip is the sum of the time spent running and stopped.

TABLE 13. - Summary of stop-and-go operation of truck
(Dry road, moderate temperature, 60-psig tire pressure, 868-lb payload)

Trip number	186, 191, 196, 202		193, 194, 198		188, 189, 209		192, 195, 205, 231	
Stops per mile	3/4		5		5		7-1/2	
	Average	Estimated standard deviation	Average	Estimated standard deviation	Average	Estimated standard deviation	Average	Estimated standard deviation
Trip data:								
Length of stops....min....	0.5	-	0.5	-	1.5	-	0.5	-
Total time of stops....hr....	.125	-	.83	-	2.50	-	1.25	-
Running time....hr....	1.09	-	1.33	-	1.40	-	1.52	-
Total trip time....hr....	1.215	-	2.16	-	3.90	-	2.77	-
Average running speed....mph....	18.3	0.4	15.0	0.2	14.3	0.4	13.2	0.06
Gross haulage....ton-miles....	55.38	-	55.38	-	55.38	-	55.38	-
Ampere-hours used....	101.8	1.9	143.7	2.1	147.0	1.7	160.8	1.3
Charging data:								
Time....hr....	17	-	17	-	17	-	17	-
Input, ac kwhr....	15.1	.4	18.9	.4	19.9	2.2	21.0	.9
Input, dc kwhr....	11.9	.4	15.3	.3	15.9	1.9	17.0	.7
Specific gravity at 77° F, points increase..	64.5	6.8	81.3	2.6	84.3	6.4	94.3	4.6
Performance:								
Ton-miles per ac kwhr....	3.67	.09	2.92	.06	2.80	.29	2.64	.11
Miles per ac kwhr....	1.33	.03	1.06	.02	1.01	.10	.953	.041
Miles per ampere-hour....	.197	.004	.139	.002	.136	.002	.124	.001
Miles per specific gravity, points increase.	.313	.032	.246	.008	.238	.019	.213	.010

Trip number	190, 194, 200, 204		187, 208, 211		201, 206, 212	
Stops per mile	7-1/2		10		10	
	Average	Estimated standard deviation	Average	Estimated standard deviation	Average	Estimated standard deviation
Trip data:						
Length of stops....min....	1.5	-	0.5	-	1.5	-
Total time of stops....hr....	3.75	-	1.67	-	5.00	-
Running time....hr....	1.53	-	1.70	-	1.69	-
Total trip time....hr....	5.28	-	3.37	-	6.69	-
Average running speed....mph....	13.1	0.18	11.8	0.18	11.8	0.29
Gross haulage....ton-miles....	55.38	-	55.38	-	55.38	-
Ampere-hours used....	165.3	2.1	178.7	6.0	184.0	2.6
Charging data:						
Time....hr....	17	-	17	-	17	-
Input, ac kwhr....	21.3	.7	22.8	2.0	23.5	.9
Input, dc kwhr....	17.0	.3	18.4	1.6	18.8	.2
Specific gravity at 77° F, points increase..	93.8	4.0	104.3	5.5	110.0	4.4
Performance:						
Ton-miles per ac kwhr....	2.60	.08	2.44	.21	2.36	.09
Miles per ac kwhr....	.940	.092	.880	.078	.852	.031
Miles per ampere-hour....	.121	.002	.112	.004	.109	.002
Miles per specific gravity, points increase.	.214	.009	.192	.010	.182	.007

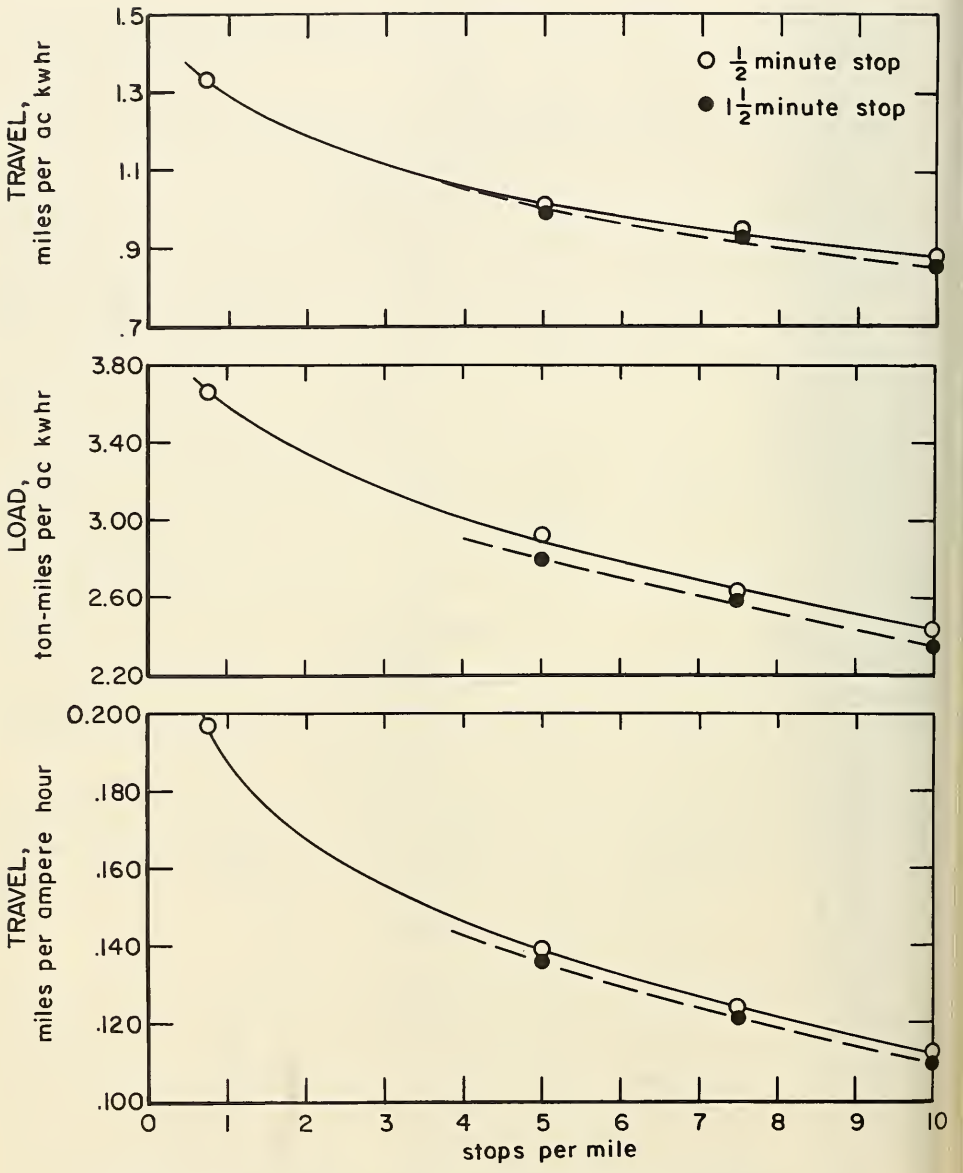

FIGURE 18. - Effect of Stop-and-Go Operation on Overall Truck Performance.

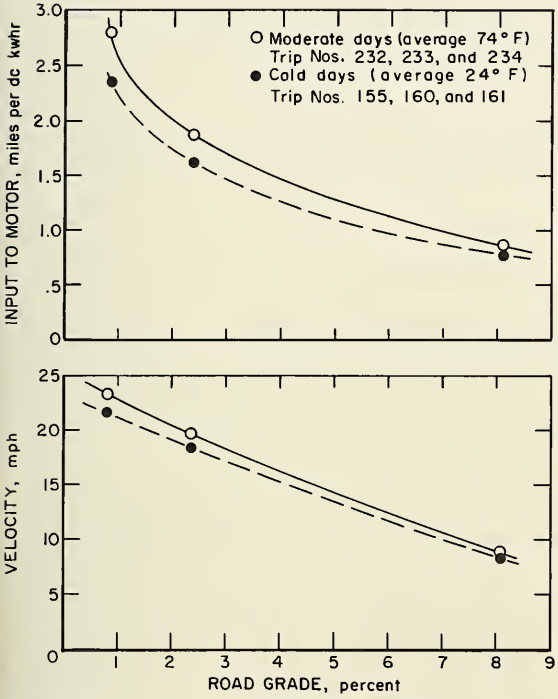
O Moderate days (average 74° F)
Trip Nos. 232, 233, and 234
● Cold days (average 24° F)
Trip Nos. 155, 160, and 161
INPUT TO MOTOR, miles per dc kwhr
VELOCITY, mph
ROAD GRADE, percent

FIGURE 19. - Effect of Atmospheric Temperature Upon Miles per dc kwhr Input and Truck Velocity.

Figure 18 shows specific mileage, specific haulage, and miles traveled per amp hr used plotted as functions of stops per mile. All curves are plotted at constant parameters of length of time of each stop.

As the number of stops per mile increased, the overall truck performance decreased greatly (fig. 18). For example, for 1/2-minute stop periods, and as the stops per mile increased from 3/4 to 10 stops per mile, the ton-miles per ac kwhr input decreased from 3.67 to 2.44 for a 33.6 percent decrease. The other measures of overall performance, such as miles traveled per ac kwhr input and miles traveled per amp hr used, declined similarly.

The length of stop produced small but significant changes in the truck performance. As shown in figure 18, at 10 stops per mile truck performance decreased by about 3.3 percent from 2.44 to 2.36 ton-miles per ac kwhr, as stop time increased from 1/2 to 1-1/2 minutes. The cause of this trend, which is found in the other performance factors, is not known.

Effect of Temperature

As the weather became colder, slight decreases in truck velocity were sensed by the driver. To verify the existance of a temperature effect, instantaneous recordings of data during days of cold and moderate temperature were compared. Figure 19 shows the velocity and the miles traveled per dc kwhr input as functions of percent road grade for a series of trips on cold and moderate temperature drop. Cold days are days with temperatures below 40° F; moderate days have temperatures from 40° to 80° F. The curves in figure 19 show that as the average atmospheric temperature dropped from 74° to 24° F, it resulted in a decrease in average truck velocity and in miles traveled per dc kwhr input from the battery. On the 2.37-percent grade test strip, the resulting decreases in truck velocity and in miles traveled per dc kwhr input amounted to 6.1 and 13.4 percent, respectively. These decreases in truck performance are partially attributed to increases in internal resistance of the

lead-acid battery. The lower temperatures increased the battery resistance; while driving on the 2.37 percent grade test strip, the average discharge voltage was higher on moderate days (65.2 volts) than it was on cold days (63.4 volts).

Decreased mechanical efficiency due to increased viscosities of lubricating material also contributed to less efficient truck operation in colder weather.

MAINTENANCE

Electrical System

Maintenance of the electric truck was generally simple. Two major breakdowns in the electrical system occurred during the course of the experimental program. The first major electrical breakdown occurred during trip No. 7, when the motor sustained a short circuit across the armature coils. This malfunction arose from a manufacturing defect in the motor. Two weeks of operation were lost while factory repairs were being made on the motor.

The other major electrical failure occurred after 5,133 miles of operation when one of the carbon brush holders became wedged in the commutator and consequently gouged the surface of the commutator. After the commutator surface was repaired, several sets of carbon brushes (55/32-inch initial length) were tried on the motor, and were found to wear very rapidly, even though the commutator surface had been thoroughly polished. The rate of wear of the new brushes was about 3/32 inch per 100 miles traveled, or 14.3 percent per 100 miles, based on an arbitrary usable wearing length of 21/32 inch. The overall rate of wear of the original set of brushes was much lower than 3/32 inch per 100 miles: about 0.4/32 of an inch per 100 miles traveled. The new brushes, therefore, were wearing over seven times faster than the normal rate.

To follow more closely the rate of wear on the new brushes, a new set of brushes was installed at 5,684 odometer miles and periodic measurements were taken of available length. Plotted in figure 20 are measurements of the available usable length of the brush elements of the top brush as a function of miles traveled. Since the brushes had dual carbon elements, the element nearest the armature winding was called the back brush element; the other was called the front brush element. Measurements of brush length were taken only on the elements of the top brush because it was the most accessible brush. Only the first 21/32 inch of brush length (out of a total of 55/32 inch) was considered as available for use, because it was felt that operation beyond this point of brush wear greatly increased the possibility of repeating the damage to the commutator from overheating of the soldered parts of the brushes.

As shown in figure 20, the back brush element started wearing immediately at a high rate of 3/32 inch per 100 miles. After 550 miles of travel, the back brush element stopped wearing and the front brush element, which had remained at its original length, started wearing at a higher rate of about 5/32 inch per 100 miles. After about 900 miles of operating using this set of brushes, the front brush element ceased wearing rapidly, and leveled out to a

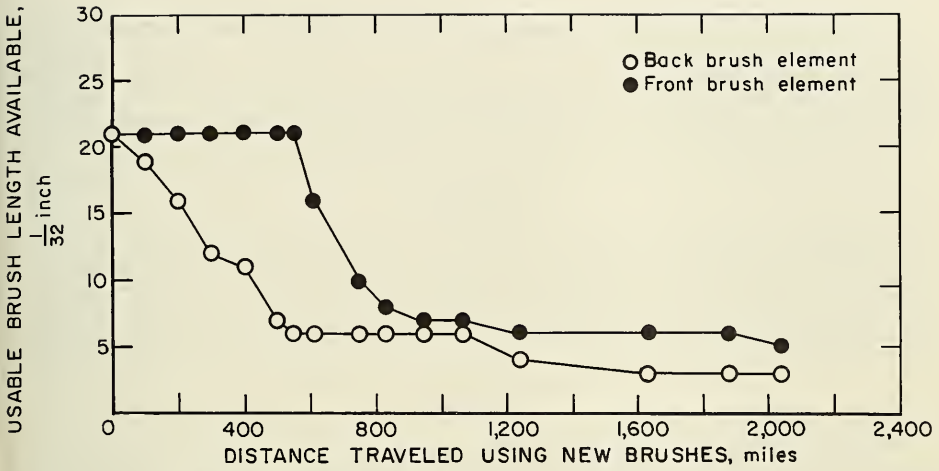

FIGURE 20. - Brush Wear as a Function of Miles Traveled.

very low wear rate of about 1/160 inch per 100 miles for the remaining 1,000 miles of test.

The pattern of brush wear as shown in figure 20 indicates that about 70 percent of the arbitrary "useful" length of a new brush can be consumed very rapidly during an initial period of "lapping in." It is likely that all of the previous sets of new brushes that initially exhibited very high rates of wear, and even the original set of brushes, underwent such a "lapping in" period.

In addition to the two major electrical breakdowns just discussed, minor electrical difficulties were also encountered and corrected. These difficulties are listed in table 14. Failure in the control circuit was caused mainly by loose connections. These were readily corrected.

TABLE 14. - List of electrical difficulties encountered at various odometer readings

Odometer miles	Item
1	Three forward relay coils burned out.
253	Shorted armature coils in the electric motor.
355	Loose connection on forward contactor.
797	Loose connection on reverse contactor.
2,979	Control circuit failure.
3,204	do
3,213	do
5,133	Start of brush wear problem.
5,811	Control circuit failure.

The item receiving the highest frequency maintenance was the motive battery. Battery care involved daily checking of connections, specific gravity readings, and the washing off of the tops of the battery. In normal operation other than experimental, a weekly or perhaps a biweekly check of these items would suffice. Addition of distilled water to the cells was required about every 16 trips. About 1.2 gallons of water was used per filling.

Mechanical

Mechanical care of the truck was simple. The truck was lubricated at 2,239 and 4,731 odometer miles. Transmission oil was changed for summer and winter driving, S.A.E. 140 grade for summer and S.A.E. 90 for winter. At 4,731 miles, an inspection of the brake shoes indicated more than 75 percent of the original lining remained. Two flat tires resulted from foreign objects on the roads.

CONCLUSIONS

To determine the overall energy efficiency of the truck experimentally would have required measurement of the energy expended either at the motor shaft or at the drive wheels for the length of an entire trip. Since this was not done, the overall efficiency of the Bureau's truck can only be approximated from an estimate of the various efficiencies of the pertinent truck components, such as charger, battery, motor, and gears. For operation over standard course No. 1 at standard conditions, the overall energy efficiency of the truck was estimated roughly to be 40.9 percent. (See appendix for calculation.) Except for changes in the number of stops per mile, changes in driving conditions will only impose small changes in the overall energy efficiency of the truck.

At a meter rate of 2.25 cents per kwhr at the line, and at a mileage of 1.5 miles per ac kwhr (table 9), cost of power per mile over course No. 1 at standard operating conditions amounts to 1.5 cents per mile.

When the Bureau truck made a large number of stops per mile, for example, 10 or more, the miles traveled per ac kwhr decreased from 1.5 to about 0.85 (fig. 9). This change increases the energy cost to (2.25/.85) or 2.65 cents per mile. If gasoline costs 29 cents per gallon, the mileage on a gasoline-powered vehicle in stop-and-go delivery service would have to be 11 miles per gallon to achieve a fuel cost of 2.65 cents per mile. According to Nicholson and coworkers,[5] the average mileage of a 4-cylinder home delivery truck in daily stop-and-go service is about 5 miles per gallon. At a gasoline cost of 29 cents per gallon, the corresponding fuel cost is 5.8 cents per mile. The energy cost of about 2.65 cents per mile for the battery-powered Bureau truck for the stop-and-go-type service within city limits compares very favorably. For a complete economic comparison, however, other cost factors such as the fixed charges and maintenance costs also would have to be considered.

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[5]Nicholson, Charles V., H. C. Riggs, and Norb Leinen. Electric Trucks Take Over Short-Route Runs? Food Processing, v. 22, No. 3, March 1961. pp. 35-37.

According to Nicholson and coworkers, these factors also are favorable for the electric truck.

An interesting comparison also can be made of the performance of the Bureau truck on course No. 1 against an evaluation by Erikson[6] of a hypothetical 2-passenger battery-powered car. The hypothetical car weighed a total of 2,250 pounds. This weight included 300 pounds for the passengers and 1,000 pounds for the battery. The car was considered for driving only within city limits, and it had a range of 54 miles at 25 mph on a level road. The overall efficiency was 43 percent, which included 95 percent efficiency for the motor controller. At meter charge of 2.25 cents per kwhr, the energy cost for the car was about 0.7 cent per mile. Considering that the gross weight and the standard payload of the Bureau truck were, respectively, 2.1- and 2.6-fold greater than that of the hypothetical car, the fuel economy of the Bureau truck over the rather hilly course No. 1 at 1.5 cents per mile is about equivalent to that of the hypothetical passenger car.

Basic traction relations show that the energy (and hence, the cost) per mile traveled can be lowered by an increase in efficiency and/or a decrease in gross weight. On the other hand, specific haulage, the ton-miles obtained per unit energy input, can be improved only by an increase in efficiency. Increasing of efficiencies in electric vehicles, therefore, is as urgent as reducing vehicle weights.

In actual practice, however, driving within city limits today commonly involves periods of travel over high-speed throughways where the prevailing speed may be 50 mph or more. Calculations by Erikson indicated that an increase in the speed of a vehicle from 25 mph to 50 mph increased the theoretical power requirements about 3.8 fold. An increase of this magnitude is therefore needed in present-day motive battery capacities if the battery-powered vehicle is to fulfill the important performance requirements of higher range and speed. Thus, it would appear that the use of battery-powered vehicles for extensive road travel awaits a major breakthrough in the field of reversible storage of electrical energy.

Battery-powered vehicles used in off-the-road applications such as fork-lift trucks, golf carts, and walkie trucks, are not subject to requirements of high speed and range, are already widely accepted, and are expected to grow in use. Use of battery-driven trucks in home-delivery service may also enjoy an increase, provided the advantage of the fuel economy as indicated in this study can be sustained in the overall economics of home-delivery service.

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[6]Erikson, Claud R. The Electric Auto. Proc. 22nd Ann. Meeting, Amer. Power Confer., Chicago, Ill., v. 22, Mar. 29-30, 1960, pp. 448-464.

APPENDIX. - APPROXIMATION OF OVERALL ENERGY EFFICIENCY OF TRUCK

1. Overall efficiency, e_o, is expressed as

$$e_o = e_c \cdot e_b \cdot e_m \cdot e_{ge},$$

where e_c = efficiency of charger,

e_b = efficiency of battery,

e_m = efficiency of motor plus controller, and

e_{ge} = efficiency of gear train.

2. The value of $(e_m \cdot e_{ge})$ can be estimated from the equation for tractive power required. A modification of an equation from Electrical Engineers' Handbook[7] is:

$$EI\ e_m\ e_{ge} = 2\ v\ [W(R_r + R_g) + f_A],$$

where E = motor voltage,

I = motor current,

v = truck speed, mph,

W = total or gross weight of truck, tons,

R_r = resistance of the tire on the road, pounds per ton of truck weight,

R_g = resistance due to uphill grade = (20 X percent road grade) pounds per ton of truck weight, and

f_A = air resistance in pounds, where f_a = (.00089) A v^2 for an average drag coefficient of 0.27, and A = frontal area of truck in ft^2.

The handbook indicated that rolling resistance on hard, level asphalt roads varies from 15 lb/ton for special tires to 35 lb/ton for standard passenger car tires. These values are increased by an appropriate factor according to the degree that the road is more resistant than smooth asphalt.

The truck tire resistance was assumed to be considerably lower than that of a tire on a passenger car because of the truck tires' smoother tread and higher air pressure. It was assumed, therefore, that the truck tire

[7]Pender, Harold, W. A. Del Mar, and K. McIlwain. Electrical Engineers' Handbook, John Wiley and Sons, Inc., New York, 3d ed., 1947, pp. 17-104.

resistance was about 25 lb/ton on smooth asphalt. With a factor of 1.15 for macadam road, $R_r = 25 \times 1.15 = 28.8$ lb/ton.

Since the average trip velocity was about 18 mph over course No. 1, and the 1.85:1 gear ratio was used most of the time, instantaneous operating conditions on the 2.37-percent grade were assumed to be fairly typical of the average performance over course No. 1 under standard conditions. Thus from figure 16 at 868-pound payload and 2.37-percent grade: EI = 10,400, v = 18.75, R_g = 47.4, and W = 2.77. For a frontal area of about 6 ft X 5 ft = 30 ft^2, $f_a = (.00089)(30)(18.75)^2 = 9.38$.

By substitution in the traction equation:

$$e_m \cdot e_{ge} = \frac{(2)(18.75)[2.77(28.8 + 20 \times 2.37) + 9.38]}{10,400} = 0.795.$$

Assuming 97 percent efficiency for the rear axle and 95 percent efficiency for the intermediate gearing, $e_{ge} = 0.97 \times 0.95 = 0.922$, and $e_m = 0.795/0.922 = 0.862$.

3. Table 9 shows that for standard operation over course No. 1,

$$e_c = \frac{18.0 \text{ dc kwhr}}{22.5 \text{ ac kwhr}} = 0.80,$$

and the amp hr meter correspondingly registered 171.3 amp hr.

Assuming that the average discharge voltage was 65.0 volts (equivalent to operation at 2.37 percent grade, per fig. 17), and that the amp hr meter was low by an average of 4 percent per calibrations, then

$$e_b = \frac{(171.3)(65.0)(1.04)}{(1,000)(18.0)} = 0.643.$$

Thus, for standard conditions and continuous driving on course No. 1,

$$e_o = (0.8)(0.643)(0.862)(0.922) = 0.409.$$